NASA/CR—2003-212367 MTI 94TM6

Users' Manual for Labyrinth Seal Design Model (KTK)

Mechanical Technology, Inc.
Latham, New York

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October 2005

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Prepared under Contract NAS3–25644

National Aeronautics and
Space Administration

Glenn Research Center

October 2005

Document History

During completion of this deliverable, MTI located existing code written by Raymond E. Chupp, Glenn F. Holle, and Thomas E. Scott, Allison Gas Turbine, Indianapolis, Indiana, for the Air Force (AFWAL TR–85–2103 Volume IV). The document availability was changed to EAR per DAA modified April 3, 2003, and Air Force communication WL/POTX W–PAFB dated December 11, 1992. It is included here with Air Force permission. The source and executable files for the CFD Seal Analysis Industrial Codes, of which this is a part, were released as LEW–16582 in 1998. This report was originally published by Mechanical Technology, Inc., in July 1994.

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NASA/CR—2003-212367

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AFWAL-TR-85-2103
VOLUME IV

LABYRINTH SEAL ANALYSIS
VOLUME IV - User's Manual for the Labyrinth Seal Design Model

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JANUARY 1986
FINAL REPORT FOR JUNE 1980 - MAY 1985

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FOREWORD

This user's manual describes the computer code which was developed to predict the leakage flow through labyrinth seals. This Design Model program was done under Contract AF33615-80-C-2014 for Labyrinth Seal Analysis. This contract with Allison Gas Turbine Division of General Motors Corporation was sponsored by the Air Force Wright Aeronautical Laboratories, Aeropropulsion Laboratory, United States Air Force, Wright-Patterson AFB, Ohio, with Mr. Charles W. Elrod (AWAFL/POTX) as Project Engineer. Technical coordination was provided by 1st Lt. Keith C. Topham.

This report was submitted in four volumes in May 1985. Volume I summarizes the development of the labyrinth seal Analysis Model. Volume II presents the user's manual for the Analysis Model computer code. Volume III contains the experimental results and summarizes the Design Model based on these empirical data. Volume IV, this publication, describes the computer code for the Design Model.

Publication of this report does not constitute Air Force approval of the findings or conclusions presented. It is published only for the exchange and stimulation of ideas.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The purpose of this manual is to describe the capabilities, organization and usage instructions for the computer program SEALKTK. This program calculates the leakage and pressure distribution through labryinth seals based on a detailed knife-to-knife analysis. Input data are required to describe in detail the seal geometry and the environmental conditions affecting the leakage. Output is provided in the form of leakage flow and flow resistance characteristics, i.e., flow factor versus pressure ratio. In addition, an optimization feature is included which permits the user to identify global geometric constraints and allows the code to identify an optimum seal configuration based on minimum leakage.

This volume, the USERS MANUAL, describes the Design Model with the basic equations referenced (Section 2.0), features of the Design Model computer program SEALKTK (Section 3.0), the organization of the program, and the purpose and function of each of the program subroutines (Section 4.0). In addition, this manual includes a description of the required input and resulting output data, and general features of the program (Section 5.0). Appendices are included which give the Design Model correlation equations, sample input and output data, and the program listing.

The program SEALKTK is written in FORTRAN IV language and has operated successfully on the IBM computer at Allison Gas Turbine Division, and on the CDC 7600 computer at WPAFB.

2.0 DESIGN MODEL DESCRIPTION

The labryinth seal Design Model is an expansion of the knife-to-knife (KTK) analyses reported in the literature. In such approaches, one-dimensional flow parameters in the knife throats are computed and linked together by a total pressure loss calculation. Flow coefficients are used for individual knives or groups of knives to account for the vena contracta in knife throats. Velocity head carry-over from upstream knives is accounted for by reducing the head loss between knives based on the flow expansion angle.

The Design Model is similar to previous KTK approaches except that the loss for each knife is broken down further into three losses as shown in Figure 1:

- contraction - stations 1 to 2 and 4 to 5
- venturi and friction - stations 2 to 3 and 5 to 6
- partial or full expansion - stations 3 to 4 and 6 to 7

This detailed pressure loss approach is consistent with current Allison Gas Turbine design practices for internal flow systems for many types of flow geometries. The three loss coefficients aid in understanding the effects that each seal parameter has on the pressure drop across a knife. They reflect the types of pressure drops that the flow experiences more specifically than a knife flow coefficient used in previous KTK models. Specifically, the Design Model consists of:

- one-dimensional flow calculation at three locations for each knife

- calculation of the individual loss coefficient values from the flow and geometric conditions

- correction of loss coefficient values due to the presence of adjacent knives

- linking of the total pressure between stations based on the total pressure drop from the loss coefficient and local velocity head

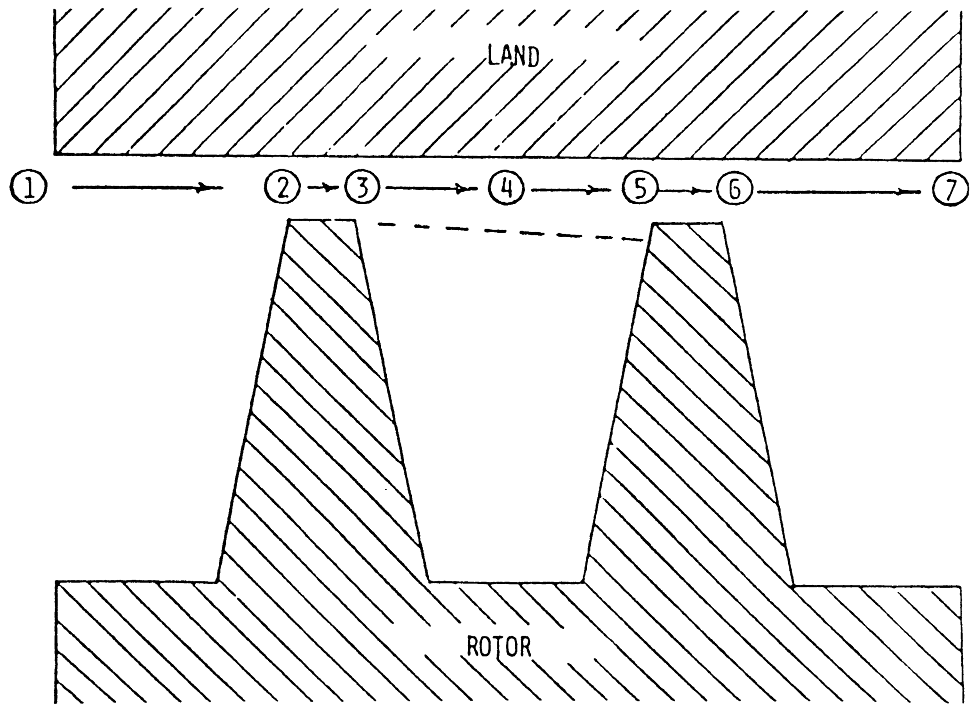


Figure 1 Seal loss zone schematic

Figure A-1 in Appendix A lists the basic flow equations used in the Design Model.

Early in the development of the design model, knife loss coefficients were specified in the input data. The loss coefficients were then corrected by applying the model to the data base. The corrected coefficients were correlated against the independent seal parameters using a linear regression analysis. This iterative process was continued until equations were obtained which, not only, fit the data but were also physically relevant. The correlating equations were put into the model code and then the model accuracy was assessed by comparing the calculated flow results with the flow results in the entire data base.

Detailed information about the Design Model is given in Ref. (9) and is summarized in the following paragraphs. This includes a discussion of the parameters considered and the model development for single knives, straight seals and stepped seals.

2.1 PARAMETERS CONSIDERED

Based on the literature survey and previous experience at Allison, Ref. (9), the parameters selected for consideration in the Design Model were those listed in Table 1. Schematics are given in Figures 2 and 3 which define these parameters. The effect of rotational speed was not included because of the lack of accurate, and complete experimental data for labyrinth seals at knife tip speeds typical of those found in gas turbine engines.

The parameters listed in Table 1 were incorporated into the model to define the seal geometry. The geometric parameters were combined to obtain the data correlations in a manner that would make the correlations physically relevant. The ranges of these geometric parameter combinations in the data base are given in Table 2. The Design Model is valid primarily within these ranges.

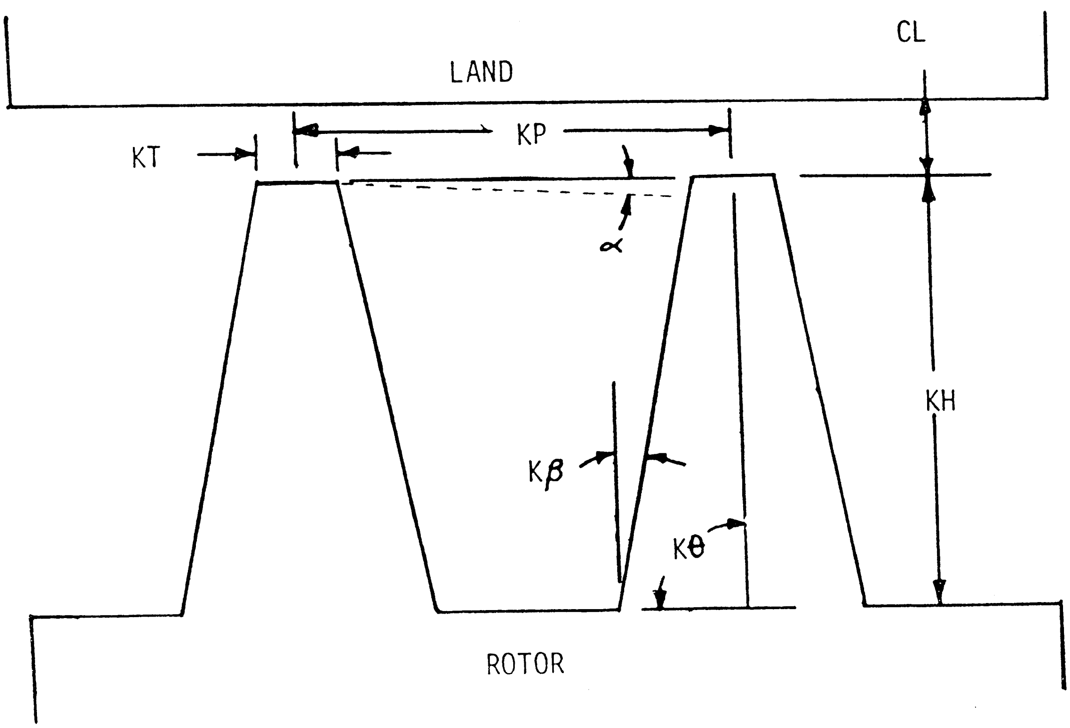


Figure 2 Seal nomenclature for straight seals

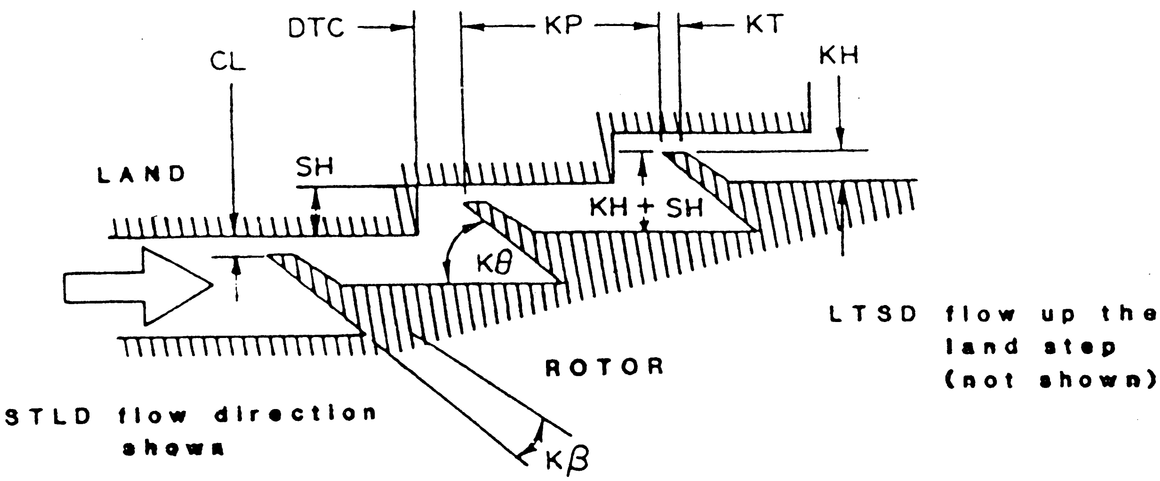


Figure 3. Seal nomenclature for stepped seals

Table 1.

Parameters in the Design Model

Geometric parameters for straight and stepped seals

- o Knife height (KH)
- o Knife pitch (KP)
- o Number of knives (KN)
- o Knife angle (Kθ)
- o Knife tip thickness (KT)
- o Knife taper angle (Kβ)
- o Knife tip leading edge radius (KR)
- o Clearance (CL)
- o Surface roughness (ϵ)

Additional parameters considered for stepped seals

- o Step height (SH)
- o Distance to contact (DTC)
- o Flow direction (LTSD or STLD)

Flow parameters

- o Overall pressure ratio (P_R)
- o Inlet stagnation pressure (P_U)
- o Fluid temperature distribution (T)
- o Flow rate (w)

Table 2.
Parameter ranges of data in labyrinth seal data base.

		Seal type		Stepped seal	
Parameter		Single knife	Straight seal	STLD dir.	LTSD dir.
KN	min	1	2	2	2
	max	1	12	6	6
KT/CL	min		0.21	0.21	0.50
	max	3.3	4.4	2.64	1.50
Kθ	min	30	60	50	50
	max	90	90	90	90
KH/CL	min	–	2.7	5.1	5.1
	max	–	31.3	29.4	28.0
KP/CL	min	–	4.0	6.4	9.2
	max	–	56.3	53	40
ε/(2CL)	min	0	0	0	0
	max	0	0.030	0	0.030
SH/CL	min	–	–	2.0	4.0
	max	–	–	29.4	12.5
DTC/CL	min	–	–	0.85	4.1
	max	–	–	40	19.4
(KP-KT)/CL	min	–	3.5	6.2	8.9
	max	–	55.0	51.8	38.5

2.2 SINGLE KNIFE

Analyzing flow data for a single knife affords the advantage of isolating the individual knife losses from the influence of adjacent knives. For the Design Model approach the three loss coefficients for the knife were separated using overall flow characteristic data. This was done by first noting that the expansion loss (K_e) would be unity because of the complete expansion downstream of a single knife. The other two loss coefficients, contraction (K_c) and venturi with wall friction (K_{vf}), were separated by considering data from several authors who varied the leading-edge sharpness and the thickness of the knife tip independently. It was assumed that the leading-edge radius affected only K_c and that the knife tip thickness affected only K_{vf}. The resulting correlations for K_c and K_{vf} are given in Figures A-2 and A-3 in Appendix A. In these correlations, the local flow factor, ϕ, is an independent parameter. Several values for knife tip radius (KR) are listed in Figure A-2 from the five data sources.

Single knife flow data for slanted knives were also analyzed to determine the effect of knife angle. Figure A-2 gives the results. For $K\theta < 90$ deg, it was found that a parametric function of $K\theta$ added to K_c for a 90 deg knife gave the best fit of the data. For $K\theta > 90$ deg, i.e., $K\beta = 0$, data from Idel'chick (1) indicated that a multiplier applied to K_c for a 90 deg knife would be the most appropriate.

The relationships for the three loss coefficients as summarized in Figure A-2 represent one approach that could be taken to correlate overall flow characteristics of single knife data. In combination, they accurately define the overall flow characteristics for the data sources and parameter ranges considered. The individual correlations involve the interactions of seal geometry with the flow parameters in a physically realistic way so that the overall results are valid for interpolated and some limited extrapolated data.

2.3 STRAIGHT SEALS

Multiknife seals are analyzed in the Design Model by linking the triplet losses for each knife in series so that a seal has a total of 3 times KN losses. The overall pressure loss is a summation of the individual total pressure losses. The losses are calculated sequentially starting with the known inlet pressure because the loss coefficients and Mach number are functions of the local total pressure through the parameter ϕ. For a straight seal, there is a carry-over of the velocity head from one knife to the next. This carry-over affects the K_{vf} and K_e of the upstream knife and the K_c and K_{vf} of the downstream knife. Thus, all the loss coefficients of a multiknife straight seal are influenced except the K_c of the first knife and the K_e of the last knife. The approach followed in multiknife seals is to determine the three loss coefficients for a given knife location from single knife correlations (Figure A-2) and then correct them for the influence of adjacent knives. The correction is based on the characteristics of the expansion angle of the jet discharging from the clearance gap over a knife. This approach has been discussed by Abramovich (2) and utilized by Komotori and Miyake (3) in their KTK model. Figure A-4 shows a schematic of a straight seal with the expansion angle, α, defined. The flow expands until it impinges on the front edge of the next knife. The maximum downstream flow height is CL + δ so that the expansion area ratio is (CL + δ)/CL instead of (CL + KH)/CL if the next knife were not present. This jet expansion ratio not only represents the amount the flow expands from the upstream knife but also the contraction into the downstream knife gap. The equations for δ in terms of α and the other geometric parameters are given in Figure A-4.

To incorporate the effect of α on the three loss coefficients, relationships given in Figure A-5 were used which are recommended in the literature (4) for various types of losses. The ratios A_0/A_1 and A_0/A_2 are simply the ratio CL/(CL + δ) relative to the upstream and downstream sides of a given knife, respectively.

The expansion angle, in general, will vary from knife to knife because the pressure ratio varies. This was observed in the flow visualization test results. This expansion angle variation however was not modelled because of the lack of good, complete seal data with interknife pressure data. Future Design Model development could be done to include variation through the seal based on results from Analysis Model calculations and/or test data.

The equations in Figures A-4 and A-5 were incorporated into the Design Model with α as an input value. Results were then obtained for the straight seal geometries in the data base using a range of α values. Comparing model results with the test performance data yielded the correct α values. Table 3 summarizes the range of values obtained from the various data sources. The α range obtained from Komotori's data (3) compares well with the value of 6 deg reported in a discussion of their paper. A linear regression analysis was performed on the α results. The equation obtained is given in Figure A-6.

Table 3.

Expansion angle (α) determined by correlation.

o Caunce and Everett, 6 knife	=	6 – 8 deg
o Komotori 2, 4, 8, and 10 knife	=	4 – 6 deg
o AGT 4 knife	=	2 – 4 deg
o AGT 8 knife	=	4 – 5 deg
o AGT 4, 5 knife slanted	=	2 – 4 deg

The effect of land roughness was included in the model by adding a frictional head loss term to the venturi with a wall friction loss coefficient (K_f) in the model for a smooth land (see Figure A-6). Also, the flow area in each knife throat was increased to account for the increase in clearance due to the land roughness. The frictional head loss coefficient was determined from published rough-pipe turbulent flow friction factor correlations and a length equal to the knife pitch for knives 2,3, and equal to knife-tip thickness for the first knives.

2.4 STEPPED SEALS

Stepped seals are designed to minimize carry-over from one knife to the next. Accordingly, one model approach could be to simply derive a new correlation for the expansion angle in terms of cavity dimensions. This method however is not acceptable because stepped seals flow both more and less than equivalent straight seals without carry-over depending primarily on the clearance. An expansion angle approach can only account for a flow equal to or greater than that without carry-over.

Physically, the flow between knives in a stepped seal does carry-over some of the velocity head to the next knife. But while the intervening flow path dissipates some of the velocity head it also affects how the flow enters the next knife and thereby influences the loss coefficients of that knife. The complex flow patterns involved would make correction correlations to the loss coefficients difficult to determine accurately. Consequently, a simpler approach was taken to introduce an area correction factor (XMUL) for a knife throat downstream of a step. This factor is a multiplier on the flow area and can be less than or greater than unity. It accounts for carry-over, additional pressure loss in flowing between the knife face and step which is important for small distances to contact (DTC), and flow distortion into the next knife throat.

A correlation for XMUL was obtained through a procedure similar to that followed for α for straight seals. Model results were calculated for stepped seal configurations in the data base for a range of inputted XMUL values. Comparing these results with test data yielded the correct XMUL value. The area multiplier was found to vary from 0.55 to 1.32. A correlating equation for XMUL in terms of the various geometric parameters was derived using a linear regression analysis. This was done first for STLD flow direction, backward facing stator steps, because there were 62 configurations for STLD flow direction compared to 15 for LTSD flow. A correlation for the LTSD flow direction was obtained by comparing the STLD equation to the LTSD data and deriving a correction expression. This approach gives the best chance to extrapolate the narrower parameter ranges for the LTSD data. Figure A-7 gives the two correlating equations for XMUL and respective parameter ranges.

Roughened surface land effects for stepped seals were handled in the model using a procedure similar to that used for straight seals, i.e., adding a friction head loss term to K_{vf} for a smooth wall plus increasing the throat area due to roughness. However, the length of the roughened passage was taken to be the knife-tip thickness to give the best agreement between the model and test data.

2.5 DESIGN MODEL OPTIMIZATION

The Design Model is an abbreviated analysis tool. Design is typically accomplished using this model by: (1) determining the overall design constraints, (2) selecting the allowable range of each parameter to meet design and model constraints, (3) using the Design Model to calculate the leakage flow rate for a matrix of possible seal configurations, and (4) optimizing the seal design from the performance matrix, i.e, finding the seal geometry with the lowest leakage. This process has been automated by coupling the Design Model with a numerical optimization algorithm. As a result, a minimum amount of input information is needed to optimize a seal configuration using the Design Model. In this section of the report, a brief description will be given for the parameters considered in the optimization algorithm.

2.5.1 Optimization Parameters

The parameters considered in the optimization code are listed in Table 4. The parameters are of three types: (1) input parameters which define the seal configuration but are not optimized, (2) optimized parameters, and (3) constrained correlation parameters. The input parameters are not optimized because of their nature (T, P_1, P_R) or the design defines their value (CL, KR, Kθ, L_{max}, H_{max}, DTC, DIA, KP_{min}). The parameters L_{max} and H_{max} are optional and constrain the calculations only if inputted. The optimized parameters listed in Table 4 are of two types: continuous and discrete. These types are handled differently by the optimization algorithm. The third type of parameter constrains the selection of the best design so that the various correlations in the Design Model are not extrapolated.

Table 4.
Design model optimization parameters

Input Parameters	Optimized Parameters
Straight and Stepped Seals	**Continuous Variables**
Clearance (CL)	Knife height (KH)
Temperature (T)	Knife pitch (KP)
Inlet total pressure (P_U)	Knife tip thickness (KT)
Pressure ratio (P_R)	Knife angle ($K\theta$)
Knife radius (KR)	Roughness (ε)
Knife taper angle ($K\beta$)	Step height (SH)**
Maximum axial length (L_{max})*	
Stepped Seals Only	**Discrete Variables**
Maximum seal height (H_{max})*	Seal type (straight, stepped)
Distance to contact (DTC)	Number of knives (KN)
Maximum or minimum diameter (D_{max}, D_{min})	Flow direction (LTSD, STLD)**
Minimum knife pitch (KP_{min}) (= 2X maximum allowable axial travel)	

* Optional

** Stepped seals only

Constraining Correlation Parameters

Straight Seals	Stepped Seals
KT/CL	KT/CL
$K\theta$	$K\theta$
(KP-KT)/KH	(KP-KT)/KH
(ε - 30)/CL	DTC/CL
	SH/CL
	KH/CL
	(ε - 30)/CL

2.5.2 Optimization Algorithm

Determining the best seal design is an iterative selection procedure which is the subject of a branch of mathematics known as optimization theory. The characteristics of the problem solved determine the type of theory; the most general is nonlinear constrained optimization. In this case, a nonlinear objective function is optimized with respect to the design requirements, also called independent variables or parameters, that are subject to equality or inequality constraints which are also nonlinear functions of the independent variables. The method selected for the Design Model Optimization code involves the use of a penalty function to convert the constrained optimization problem into an unconstrained one which is solved using the Fletcher-Power-Davidon variable metric method. This algorithm includes a parabolic cubic spline fit search routine to locate the optimum. This approach is reliable even for erratic functions often encountered in design problems.

The optimization algorithm described applies only to continuous variables, i.e., the first six optimized parameters listed in Table 4. The discrete variables were optimized by trial and comparison in which the entire matrix of these variables is considered. The code performs the continuous variable optimization for each set of discrete variable values and the overall optimum design is selected from the individual optimum designs.

Constraints have been included in the algorithms to ensure that the optimized seal configuration satisfies the design requirements. The constraints imposed are given in Table 5. Constraints on the discrete variables (KN, seal type, and flow direction) simply limit the matrix of values considered in the trial and comparison procedure. Constraints on the other variables are imposed by adding inequality penalty functions to the functions being optimized. A penalty function equals zero if the design meets a given contraint. It is greater than zero if the constraint is violated and the penalty varies parabolically with the magnitude of the violation. Each continuous variable constraint has one penalty function associated with it.

Table 5.
Constraints imposed in Design Model optimization code.

Overall length (L_{max})*
Overall height (H_{max})*

Minimum and maximum limits for all optimized parameters, i.e.,

KH, KP, KT, Kθ, ϵ, SH, KN**, seal type**, flow direction**

Minimum and maximum limits for correlation parameters to avoid extrapolation beyond data ranges in the data base, i.e.,

KT/CL, Kθ, (KP-KT)/KH, DTC/CL, SH/CL, (ϵ - 30)/CL

* Optional constraints
** Discrete variable constraints not imposed by inequality penalty functions

3.0 COMPUTER PROGRAM FEATURES

The Design Model computer program described in this report has several features to enhance its use. The program can be run in an analysis mode by defining the labryinth seal geometry to be considered and executing the program. Also, the program can be run in an optimization mode by defining certain parameters and letting the program determine the optimum values for the remaining ones. The first mode will be referred to as the Design Model code and the second one as the Design Model Optimization code. Various features of these two parts will be described separately in the following paragraphs.

3.1 DESIGN MODEL CODE FEATURES

Features available in the Design Model code include:

- The input is abbreviated where possible.

- An override is available for many of the loss coefficient parameters.

- A function loss is available instead of, or in addition to, the three loss coefficients.

- Straight seals, stepped seals, or a mixed combination of the two can be analyzed. (Steps can be for either increasing or decreasing diameter.)

- Geometric parameter values can be varied from knife to knife.

- Two dimensional or three-dimensional seals can be analyzed. (Calculations for two-dimensional seals are important to compare model results with non-rotating labyrinth seal rigs that utilize a rectangular test section).

- Various calculation options can be selected. The program can calculate:
  - seal pressure distribution for a given flow rate
  - seal pressure distribution and flow rate for a given overall pressure ratio
  - a flow characteristic curve (ϕ versus P_R)

- o a flow characteristic curve can be punched out for input to plotting routines or to flow network solution codes.

- o a summary is printed out of the various parameters with their applicable ranges (If a parameter is outside its range, a warning message is printed, and the calculations are continued with either the input parameter value or one at the end of the range depending on whether or not extrapolation is considered acceptable for that particular parameter.)

3.2 OPTIMIZATION CODE FEATURES

The optimization code is the Design Model code coupled with a driver routine. The latter calculates the independent parameter values to be used in the Design Model to search for an optimum configuration. Features of the code are:

- o Constant geometry straight and stepped seals can be considered. However, variable parameters from knife-to-knife or mixed straight and stepped seal geometries cannot be considered.

- o Each independent parameter has a default range which may be overridden. Even the correlation parameter ranges may be overridden if desired.

- o An independent parameter may be held constant (by inputting both its minimum and maximum values equal to the one desired).

- o An optimum configuration may be determined for both seal types and both directions for the stepped seals. Any subset of these may be considered.

- o Before optimization is attempted, the parameter values and ranges are checked to be sure a solution is possible, e.g., a solution is impossible if L_{max} is less than the minimum KP divided by the maximum KN. If a solution does not exist, information is printed describing the problem and the execution of the data set is halted.

- Intermediate output information is given for each combination of discrete variables employed. This output information includes algorithm parameter values, derivatives of the optimized function with respect to each continuous variable, and comparisons of the continuous variable values with the allowable ranges.

- Final output information includes sensitivity results for each discrete variable step and summary data of the optimum seal configuration designated.

The output information not only defines the optimum seal configuration but indicates the effect, if any, of imposing each constraint. Also, the improvement in decreased leakage of the optimum configuration compared to the other possible configurations is given. This information can be used to assess the penalty caused by each limiting constraint and the penalty for choosing an alternate design.

4.0 COMPUTER PROGRAM SYSTEM CAPABILITIES FUNCTION DESCRIPTIONS

The purpose of the computer program SEALKTK is to compute leakage and internal pressure distribution for various labyrinth seal configurations. The program accomplishes this by calculating a number of dimensionless parameters from the input seal geometry description and applying these parameters to loss equations developed from correlation of empirical data. A detailed description of the equations and their derivations has been given in Section 2.0 of this report. SEALKTK can also be used to determine an optimum seal configuration.

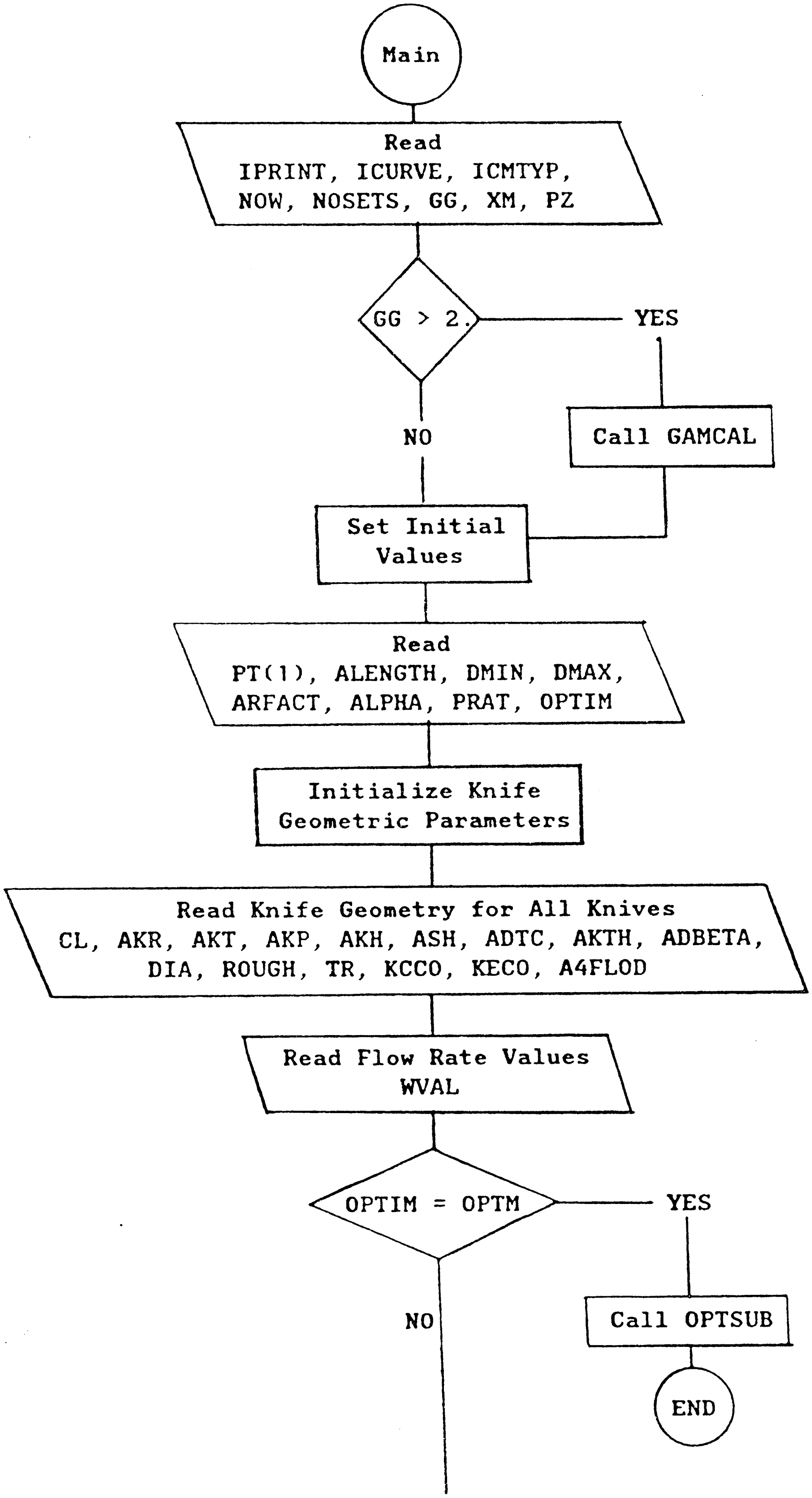
This section of the USER'S MANUAL presents a description of the computer program. Each of the subroutines is described individually and flow charts are provided to illustrate the calculation procedure.

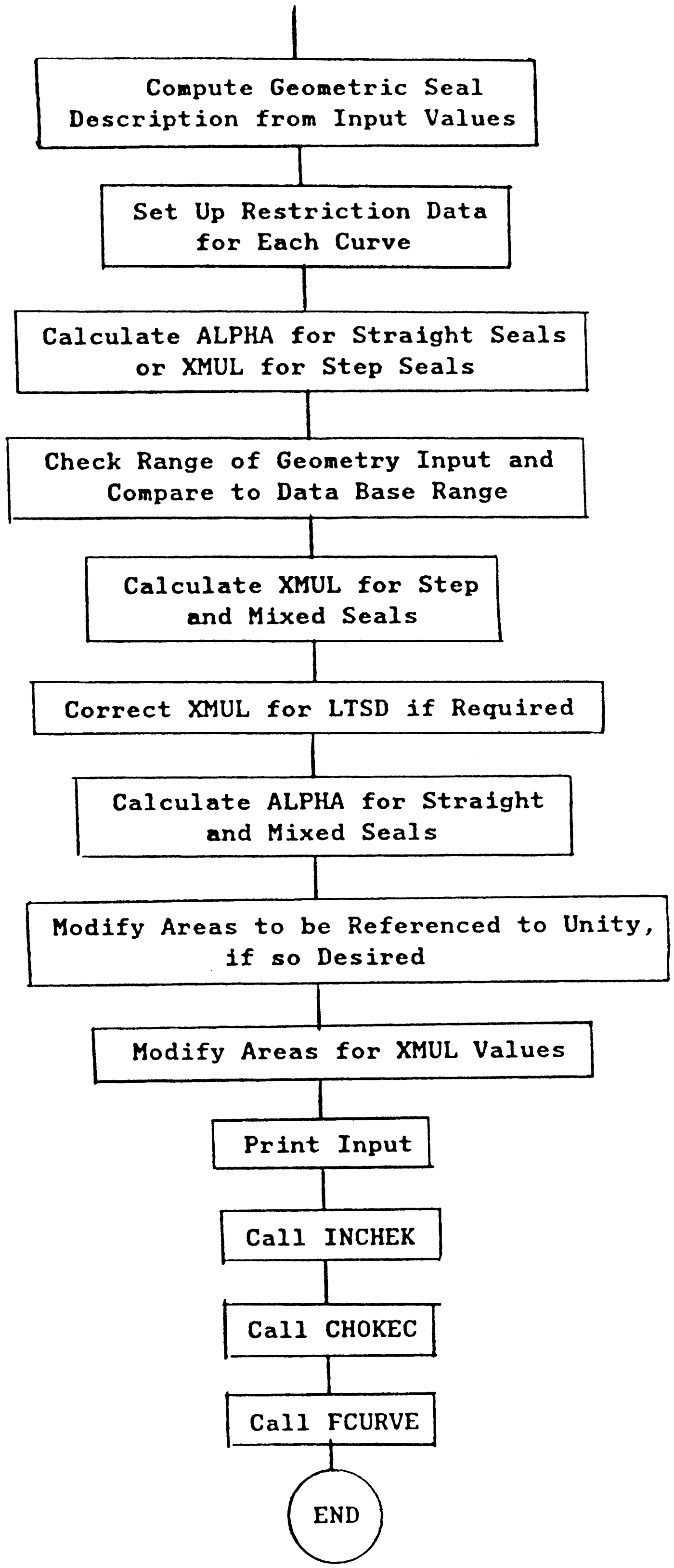
4.1 MAIN PROGRAM

The main program serves as an executive program for initialization and program control (See flow chart in Appendix D). The main program reads most of the input data and initializes seal geometric parameters. Based on the seal nondimensional parameters computed and the type of seal, straight versus stepped, the appropriate subroutines are called to obtain the loss coefficients to be used in the knife-to-knife calculation. Then the loss calculation is called to determine the leakage flow and flow characteristics (flow function versus pressure ratio) for the overall seal including the internal pressure distribution.

The input variables are defined in Section 5.0. The individual subroutines called are described later in this section.

4.1 Flow Chart

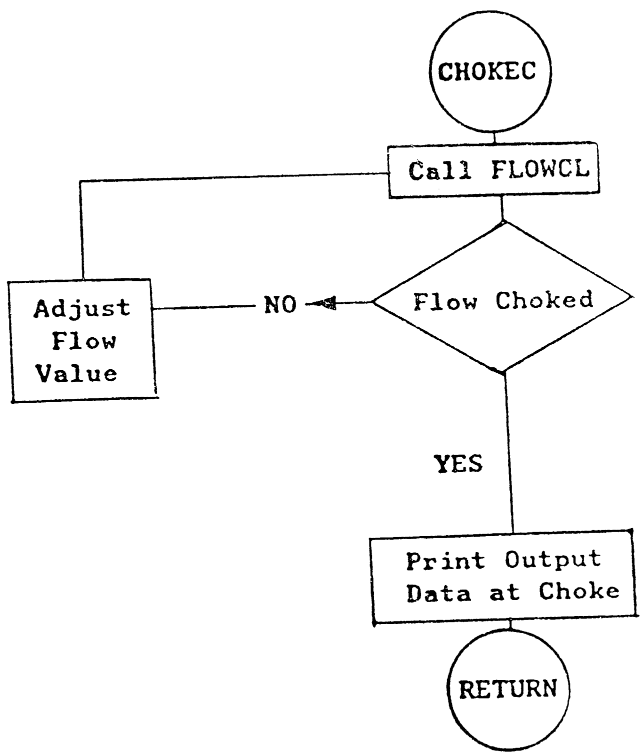



Compute Geometric Seal Description from Input Values
Set Up Restriction Data for Each Curve
Calculate ALPHA for Straight Seals or XMUL for Step Seals
Check Range of Geometry Input and Compare to Data Base Range
Calculate XMUL for Step and Mixed Seals
Correct XMUL for LTSD if Required
Calculate ALPHA for Straight and Mixed Seals
Modify Areas to be Referenced to Unity, if so Desired
Modify Areas for XMUL Values
Print Input
Call INCHEK
Call CHOKEC
Call FCURVE
END

4.2 SUBROUTINE CHOKEC

Calculation of choke point or flow to give a desired pressure ratio using the method of interval halving.

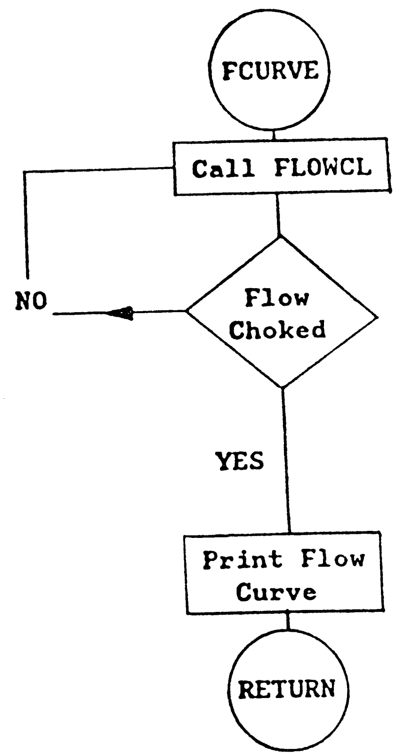
4.2 Flow Chart



4.3 SUBROUTINE FCURVE

Calculation of flow curve given the choke point.

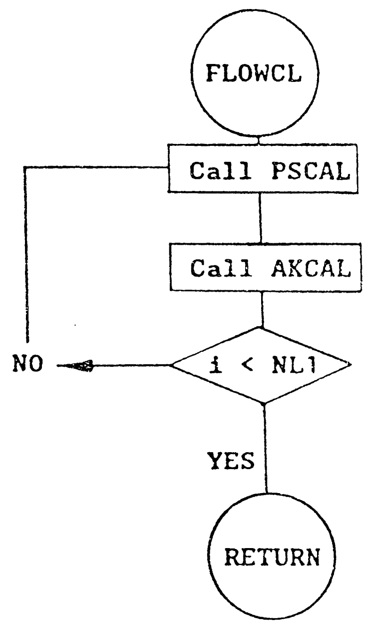
4.3 Flow Chart



4.4 SUBROUTINE FLOWCL

Calculates the resistance to flow, i.e. pressure loss, for a labyrinth seal given the flow rate.

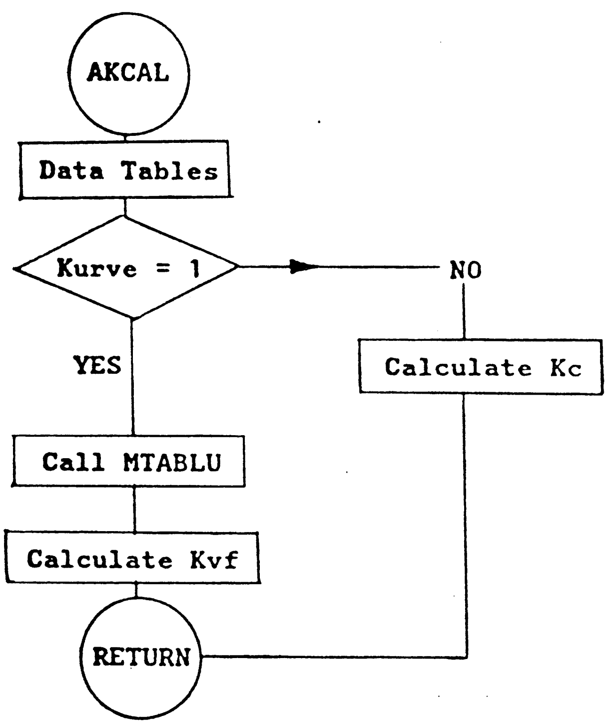
4.4 Flow Chart



4.5 SUBROUTINE AKCAL

Calculates loss coefficients for the labyrinth seal based on correlated loss parameters.

4.5 Flow Chart



4.6 SUBROUTINE PSCAL

Calculates Mach Number and static pressure.

4.7 SUBROUTINE TABLU

Performs a single table look up for y given x with extrapolation permissible if so specified.

4.8 SUBROUTINE MTABLU

Performs a multiple table look up for y given x and z with extrapolation permissible in both directions if so specified.

4.9 SUBROUTINE INCHEK

Calculation to check the range of the input geometric parameters to ascertain whether they are within the appropriate ranges for which the AMUL and ALPHA correlations are based.

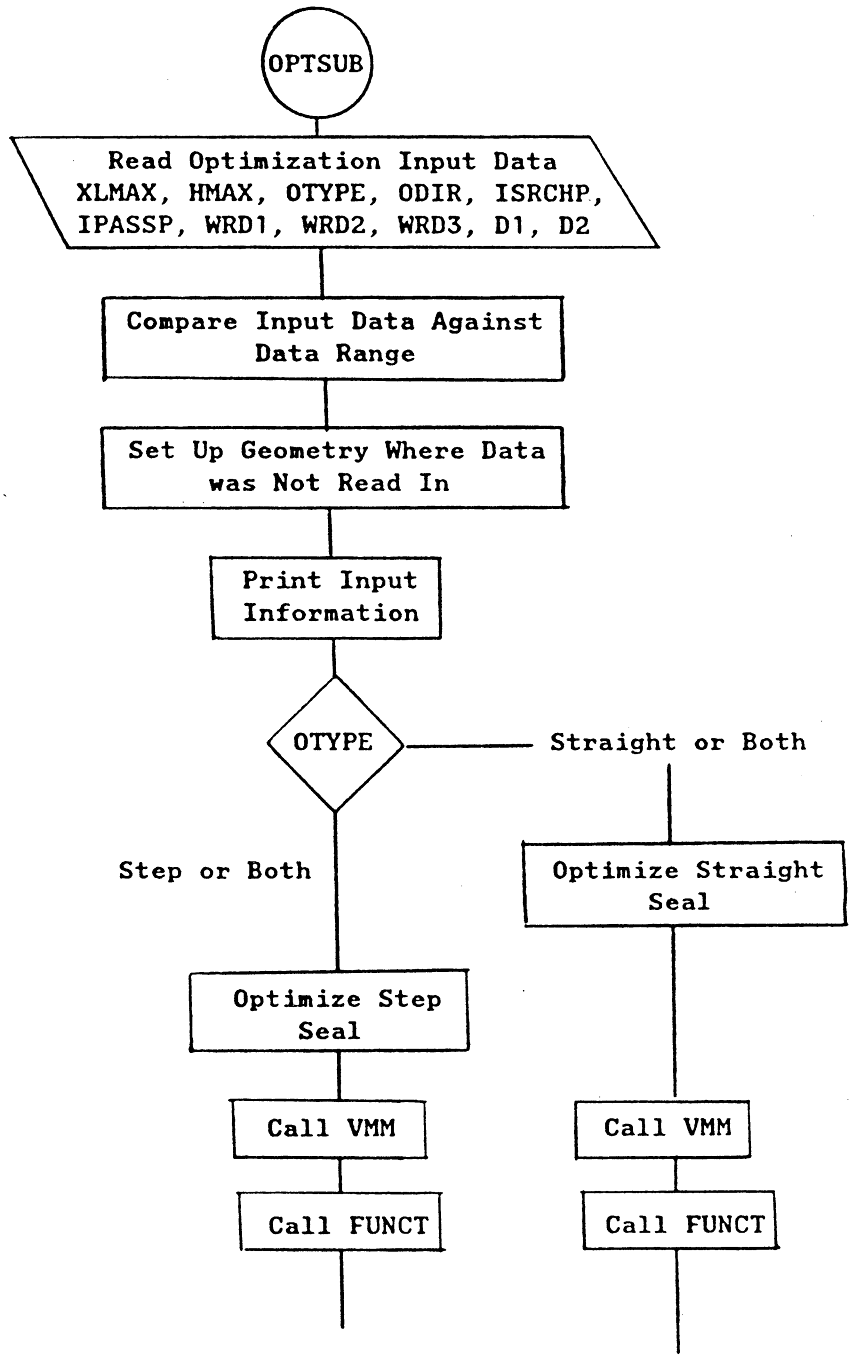
4.10 SUBROUTINE GAMCAL

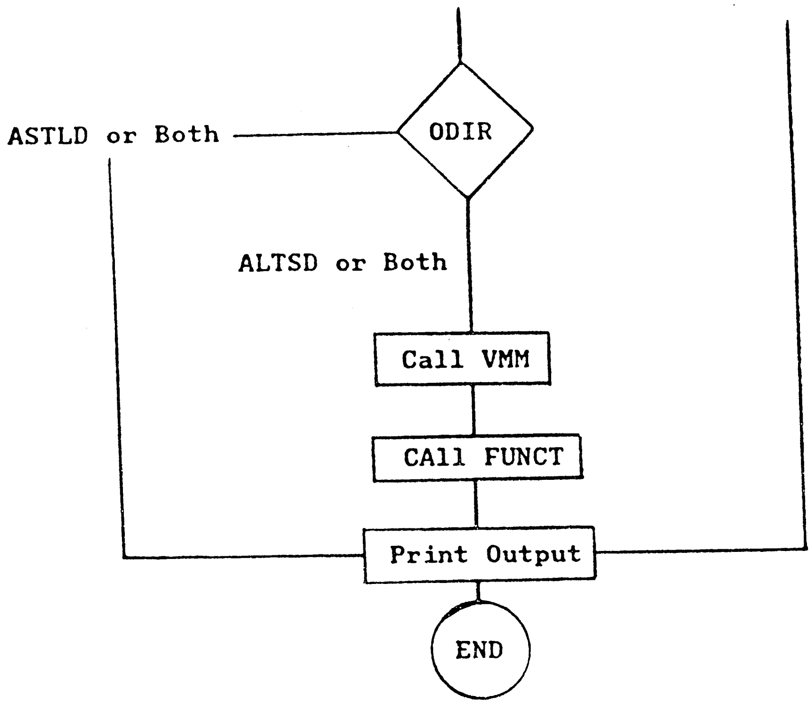
Subroutine to calculate specific heat ratio for air from curve fit EQUATIONS.

4.11 SUBROUTINE OPTSUB

Subroutine to compute the optimum labyrinth seal geometry given boundary constraints. This subroutine reads in additional data to define the optimization problem and also controls the optimization calculation.

4.11 Flow Chart





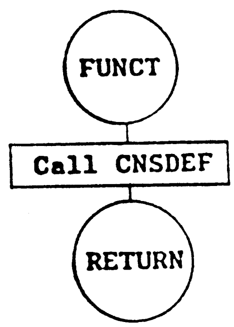
4.12 SUBROUTINE CNSDEF

Subroutine to set up the various seal parameters for each pass through the function evaluation.

4.13 SUBROUTINE FUNCT

Subroutine to compute the function to be minimized and its derivatives for a given set of parameter values.

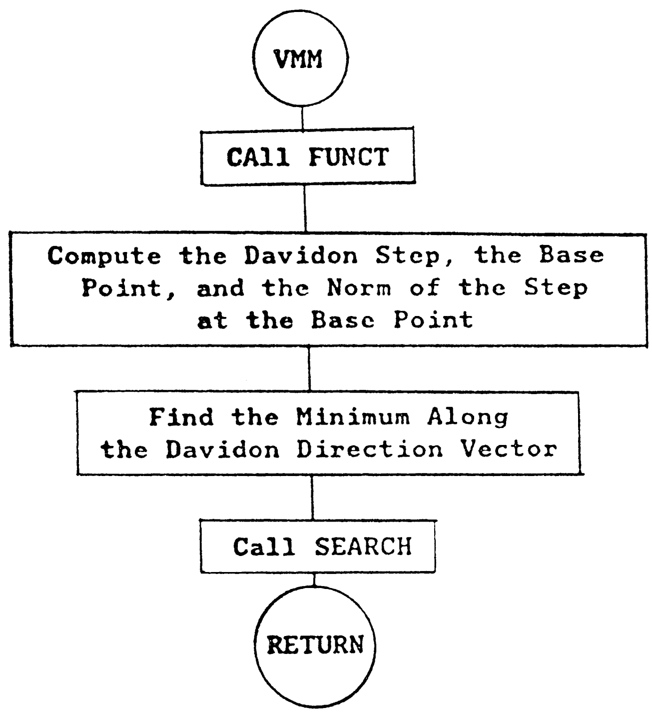
4.13 Flow Chart



4.14 SUBROUTINE VMM

Calculation of the optimum seal, i.e. minimum leakage using the Davidon variable metric method.

4.14 Flow Chart



4.15 SUBROUTINE SEARCH

Subroutine to search along a given direction of parameter changes until a minimum is located.

5.0 USAGE INSTRUCTIONS

5.1 GENERAL FEATURES

Program Language

Computer program SEALKTK has been developed and written in FORTRAN IV computer language for use on IBM and CDC computers.

Calculation Modes

As mentioned in Section 3.0, two calculation modes are available: (1) an analysis mode where all the seal geometric parameters are specified and (2) an optimization mode where certain geometric parameters are inputted and the remaining ones are determined by optimizing.

Flow Calculation Options

In the analysis mode, the flow conditons can be specified by inputting a flow rate or an overall pressure ratio, or by requesting a flow characteristic curve. In the latter, the choke point is determined by the code and then a 14 point flow characteristic curve (ϕ vs. P_R) is calculated with the choke point being the last point. In the optimization mode, a pressure ratio is specified and the optimum seal criterion is based on the minimum flow rate at the specified pressure ratio.

Seal Type Options

Straight or stepped seals can be considered with the flow going up or down the step (LTSD or STLD, respectively). For the analysis mode only, a mixed seal type can be considered which is a combination of straight and stepped seals. Also for this mode, a lip can be put in front of the first knife for a stepped or mixed seal.

5.2 Description of Input

The FORTRAN code for KTK has been modified to work with the CFD Industrial Codes framework and to compile under OS/2 using the WATCOM F77/386 compiler. The input format was changed significantly. The new Record Types are described below.

The following FORTRAN formats are used in the input:

- I5 XXXXX
- E12.4E3 +X.XXXXE+XXX
- F7.3 +XXX.XXX
- An Alphanumeric input of upto n characters

The program now requires that the input file be named KTK.INP and reside in the same directory as the executable file. The name of the output file is supplied as input using Record Type 1B.

Sample input data sets are listed in Appendix B. The output for the same data sets is listed in Appendix C.

Record Type 1A: Options Record

Variable	Columns	FORMAT	Description
IPRINT	1 - 5	I5	Print Trigger IPRINT = 0 Default > 0 Individual W printed
ICURVE	6 -10	I5	Curve Trigger ICURVE = 0 No flow curve > 0 Flow curve calculation
ICVTYP	11 - 15	I5	Print Flow Curve ICVTYP = 0 No flow curve printed = 1 Fields of 10 = 2 Fields of 5 > 2 Both
NOW	16 - 20	I5	Flow Calculation Trigger Now = 0 Choke point calculated or PR to be input > 0 NOW W values read on Record Type 6
NOSETS	21 - 25	I5	Number of data sets (Record Types 4 through 6) to be read before returning to Record Type 1A. NOSETS = 0 Return to Record Type 4A for stacked data sets NOSETS > 0 Number of data sets
GG	26 - 37	E12.4E3	Fluid Specific Heat Ratio. Default value is 1.4. If GG > 2.0, GG is used as a reference temperature to calculate the specific heat ratio.
XM	38 - 49	E12.4E3	Fluid Molecular weight. Default value is 28.97.
PZ	50 - 61	E12.4E3	Reference Pressure to calculate specific heat ratio. Default value is 14.7 psia.

Record Type 1B: Name of Output File

Name of the Output File (Upto 80 characters). The name may include a fully qualified path name but should not include the extension. The program automatically appends an extension ".OUT" to the name. For example, if the user inputs C:\MYDIR\TEST as the output file name, the program will generate output files C:\MYDIR\TEST.OUT and C:\MYDIR\TEST.FIL.

Record Type 2: First Title Record

TITLE - Title information. Upto 80 characters of alphanumeric data.

Record Type 3: Second Title Record

TITLEC - Title information. Upto 80 characters of alphanumeric data.

Record Type 4A: Knife Geometry Options and Parameters

Variable	Columns	FORMAT	Description
NOKNIF	1 - 5	I5	Number of Knives
NOKNRC	6 -10	I5	Number of knife records (Record Type 5) to be read. NOKNRC = NOKNIF Mandatory for a MIXED seal NOKNRC = 1 Constant Knife Geometry or optimization mode
TYPE	11 - 15	A5	Seal Type TYPE = 'STEP ' Stepped Seal = 'STRAI' Straight Seal = 'MIXED' Mixed Seal
DIRECT	16 - 20	A5	Flow Direction DIRECT = 'LTSD ' or 'STLD ' for STEPPED seals DIRECT = ' ' for STRAIGHT and MIXED seals
AOPT	21 - 25	A5	Area Option. AOPT = 'UNITY' Use unit area for printed PHI curves AOPT = ' ' Use calculated reference area
OPTIM	26 - 30	A5	Optimization Trigger. OPTIM = ' ' Calculation mode OPTIM = 'OPTIM' Optimization mode

Record Type 4B: Knife Geometry Options and Parameters (Cont...)

Variable	Columns	FORMAT	Description
PT(1)	1 - 12	E12.4E3	Inlet Total Pressure (psia).
ALENGH	13 - 24	E12.4E3	Seal Length (in). The seal length must be 0.0 or left blank for a MIXED seal.
DMIN	25 - 36	E12.4E3	Minimum Seal Diameter (in).
DMAX	37 - 48	E12.4E3	Maximum Seal Diameter (in). • The seal diameter may also be read on Record Type 5B. If so, that value will override DMIN and DMAX. • For a STRAIGHT seal, seal diameter DIA = MAX(DMIN, DMAX). • For a MIXED seal the diameter must be input using Record Type 5B.
ARFACT	49 - 55	F7.3	Knife radius multiplication factor. The knife radius read on record type 5A is multiplied by this number to get the actual knife radius used by the program.
ALPHA	56 - 62	F7.3	Flow Divergence Angle (deg). ALPHA is normally set to 0.0 or left blank to let the program calculate a value using semi-empirical correlations.
PRAT	63 - 69	F7.3	Overall seal pressure ratio. • PRAT may be either greater than or less than 1. If PRAT is greater than the choked pressure ratio, the output results will be for the choked pressure ratio. • PRAT must be specified for optimization mode. • PRAT is normally 0.0 or blank if ICURVE > 0 in Record Type 1A. If PRAT and ICURVE are both > 0, a flow curve will be calculated with the pressure ratio of the last point being PRAT instead of the choked value.

Records 5A, 5B, and 5C together constitute a complete set of data for specifying knife geometry. The program expects to find NOKNRC (see Record Type 4A) sets of knife geometry data.

Record Type 5A: Knife Geometry Parameters

Variable	Columns	FORMAT	Description
CL	1 - 12	E12.4E3	Radial Clearance (in).
AKR	13 - 24	E12.4E3	Knife Tip Radius (in). The actual radius used by the program is AKR*ARFACT.
AKT	25 - 36	E12.4E3	Knife Tip Thickness (in).
AKP	37 - 48	E12.4E3	Knife Pitch (in).
AKH	49 - 60	E12.4E3	Knife Height (in).
ASH	61 - 72	E12.4E3	Step Height from Previous Knife(in). STRAIGHT seals: ASH = 0.0 STEPPED seals: ASH = abs(ASH) MIXED seals: ASH > 0.0 for STLD ASH < 0.0 for LTSD

Record Type 5B: Knife Geometry Parameters (Cont...)

Variable	Columns	FORMAT	Description
ADTC	1 - 12	E12.4E3	Distance to Contact (in). The distance is specified on the upstream side of the current knife or the downstream side of previous knife. ADTC must be BLANK or 0.0 for STRAIGHT seals.
AKTH	13 - 19	F7.3	Knife Angle (deg). The angle is specified relative to the upstream surface. AKTH is 90 deg for a vertical knife.
AKBETA	20 - 26	F7.3	Knife Taper Angle (deg). If the taper angle is different on the two knife faces, then AKBETA = 2.0*upstream taper half angle.
DIA	37 - 48	E12.4E3	Knife-tip Diameter (in). • If DIA > 0.0 for STEPPED seals, the value will override DMIN and DMAX specified in Record Type 4B. • DIA must be specified for a MIXED seal.
ROUGH	49 - 60	E12.4E3	Land Roughness (υin).
TR	61 - 67	F7.3	Fluid Temperature (R).

Record Type 5C: Knife Geometry Parameters (Cont...)

Variable	Columns	FORMAT	Description
KCCO	1 - 5	I5	Carryover trigger on knife inlet side. KCCO = -1 No carryover KCCO = 1 Consider carryover KCCO = 0 Program will decide
KECO	6 - 10	I5	Carryover trigger on knife exit side. KECO = -1 No carryover KECO = 1 Consider carryover KECO = 0 Program will decide
A4FLOD	11 - 17	F7.3	Frictional loss Head factor A4FLOD = 0 No friction A4FLOD > 0 Friction loss instead of Kvf type loss

Record Type 6: Flow Rate Values

Record Type 6 is used to input a flow curve with NOW values specified in Record Type 1A. Use as many records of this type as needed to input the flow curve. This record type is required only if NOW > 0.

Variable	Columns	FORMAT	Description
WVAL	1 - 12	E12.4E3	Flow Rate (lbm/sec).
	13 - 24	E12.4E3	
	25 - 36	E12.4E3	
	37 - 48	E12.4E3	
	49 - 60	E12.4E3	
	61 - 72	E12.4E3	

Records 7 through 10 are required only if Optimization Mode - OPTIM = 'OPTIM' - is specified in Record Type 4A.

Record Type 7: Optimization Constraints

Variable	Columns	FORMAT	Description
XLMAX	1 - 12	E12.4E3	Maximum Overall Seal Length (in).
HMAX	13 - 24	E12.4E3	Maximum Seal Height (in).
OTYPE	25 - 29	A5	Seal Type to be optimized. OTYPE = 'STRAI' for Straight seals OTYPE = 'STEP ' for Stepped seals OTYPE = 'BOTH ' for both Straight and Stepped seals
ODIR	30 - 34	A5	Flow direction for Stepped seals. ODIR = 'STLD ', 'LTSD ', or 'BOTH ' for STEPPED seals ODIR = ' ' for all other seals
ISRCHP	35 - 39	I5	Extended Optimization Printout. ISRCHP = 0 Normal Printout ISRCHP = 1 Extended Printout
IPASSP	40 - 44	I5	Extended Optimization Printout. IPASSP = 0 Normal Printout IPASSP = 1 Extended Printout
IWPRNT	45 - 49	I5	Extended Optimization Printout. IWPRNT = 0 Normal Printout IWPRNT = 1 Extended Printout

Record Type 8: Optimization Parameter Limits

The optimization limits input by the user override the default values built into the program. Input only those values which are to be overridden. The program will warn you if the input values are outside the admissible range for the database of empirical data used in the program.

Variable	Columns	FORMAT	Description
WRD1	1 - 8	A8	Seal Parameter. WRD1 = 'KT' for knife tip thickness WRD1 = 'KP' for knife pitch WRD1 = 'KH/KP' for ratio of knife height to knife pitch WRD1 = 'SH' step height WRD1 = 'KTHETA' for knife angle WRD1 = 'ROUGH' for land roughness WRD1 = 'KN' for number of knives
	9 - 20		
D1	21 - 32	E12.4E3	Minimum limit.
D2	33 - 44	E12.4E3	Maximum limit

Record Type 9: Database Range Constrains

Optimization is performed within range constraints for certain parameters to ensure that the calculations remain within the range of the database used by the program. The accuracy of the design model predictions outside the database range is unknown. Therefore, modifications to the database range constraints should be done with caution.

Variable	Columns	FORMAT	Description
WRD1+WRD2	1 - 12	A8+A4	Seal Parameters. • 'KT/CL' for ratio of knife tip thickness to clearance • '(KP-KT/KH)' for ratio of knife pitch minus knife tip thickness to knife height • 'KH/CL' for ratio of knife height to clearance • 'DTC/(KP-KT)' for ratio of distance to contact to knife pitch minus knife tip thickness • 'DTC/CL' for ratio of distance to contact to clearance • 'SH/CL' for ratio of step height to clearance
WRD3	13 - 16	A4	Flow direction for STEPPED seals
	17 - 20		
D1	21 - 32	E12.4E3	Minimum range constraint.
D2	33 - 44	E12.4E3	Maximum range constraint.

Record Type 10: End of Optimization Parameter Limits

Variable	Columns	FORMAT	Description
WRD1	1 - 8	A8	WRD1 = 'END'

5.3 Description of Output

The Design Model code printed output provides a detailed description of the seal geometric parameters and the predicted aerodynamic performance. A listing of a sample output data set is given in Appendix "C". The output associated with a seal that is being optimized differs significantly from a non-optimized seal. Therefore, the two outputs will be discussed separately.

Non-Optimized Output

A description of the output corresponding to sample datasets 1 through 3 in Appendix "C" is presented in the following paragraphs. An overview is presented first, followed by a more detailed description of the output.

The first section of the output echoes some of the parameters inputted on record types 1 through 4 for quick reference. The second section, "KNIFE GEOMETRY DATA", lists the geometric parameters associated with each knife of the seal. The third section, labelled "INPUT DATA RANGE CHECK", records the results from a check of the input data against the data ranges used in the Design Model correlations. Warnings are issued when input data forces an extrapolation outside the empirical data range. If a seal parameter is outside the empirical range, this output section is printed before the first section described above. The next section of the output lists the aerodynamic parameters for each of the three flow "stations" associated with each knife. The values shown correspond to the choked flow condition unless a seal flow or pressure ratio is specified in the input. The fifth and final output section is labelled "FLOW CURVE" and prints the values which make up the flow curve for the seal (if applicable). The flow curve (a function of pressure ratio and W T/PtA) is printed out in standard and elliptical coordinates.

The "KNIFE GEOMETRY DATA" is printed for the three stations of each knife. The first sixteen column headings correlate closely with the input variable names discussed in Section 5.2 of this report. The remaining column headings, beginning with "DEL C", identify the values for other parameters determined by the code as listed below:

DEL C: Radial expansion of flow jet between knives used to calculate contraction area ratio

DEL E: Radial expansion of flow jet between knives used to calculate expansion area ratio

AREA MULT: Area multiplier on flow area for stepped seals

ALPHA: Jet expansion angle used for carry-over calculation

The "INPUT DATA RANGE CHECK" is printed after the "KNIFE GEOMETRY DATA" except when a knife parameter is outside the empirical data range. In such cases this section is printed at the beginning of the output to draw attention to the warning messages printed. The output consists of: the knife parameter being considered, the minimum value of the empirical data, the value input (or calculated) for the knife, and the maximum value of the empirical data. Asterisks are printed near the minimum or maximum value of the knife parameter when the minimum or maximum value (respectively) of the data base has been exceeded. A warning message is printed to this effect.

The fourth section of output lists the aerodynamic performance data predicted by the Design Model for each knife station. The column headings are defined below beginning with the third column.

AREA: The flow area over the knife tip calculated by the equation: $A = \pi * DIA * CL * AREA\ MULT$ (sq. in.)

TEMP: The temperature of the air entering the seal as inputted (°R)

WRT/PTA: Flow function $W * \sqrt{Tin} / Ptin * Aref$ $(lbm\sqrt{R}/sec/lbf)$

WRT/PSA: Flow function $W * \sqrt{Tin} / Psin * Aref$ $(lbm\sqrt{R}/sec/lbf)$

4FL/D: Friction factor calculated for the seal land

KFACT: Corrected dynamic head loss factor (K-factor)

LOSS TYPE: Pressure loss mechanism (sudden contraction, "long hole", sudden expansion)

PT: Total pressure (lbf/in**2)

PS: Static pressure (lbf/in**2)

MN: Mach number

KFACT METHOD: Method of calculating total pressure loss (total pressure minus static pressure or 1/2 * density * velocity**2)

PARM: Correction parameter

AMUL: Multiplier on the "XKUNC" to calculate corrected dynamic head loss factor

ADDER: Quantity added to the quantity "XKUNC" times "AMUL" to calculate corrected dynamic head loss factor

XKUNC: Uncorrected dynamic head loss factor

MOD AREA: Modified flow area calculated by multiplying "AREA MULT" (from KNIFE GEOMETRY DATA printed output) by "AREA"

The final section of printed output is labelled "FLOW CURVE" and prints the coordinates of a curve relating $W\sqrt{Tin}/PtAref$ to seal pressure ratio. Also shown are coordinates for curves relating a function of pressure ratio to functions of $W\sqrt{Tin}/PtAref$ in elliptical coordinates. Coordinates for a flow curve relating $W\sqrt{Tin}/PtAref$ and pressure ratio are also "punched" out on Fortran I/O unit 7. The row headings are defined below:

PR: Seal pressure ratio

PHI: Flow function ($W\sqrt{Tin}/PtAref$)

1.-1./PR**2: One minus the reciprocal of seal pressure ratio squared

PHI**2: Flow function ($W\sqrt{Tin}/PtAref$) squared

R/G * PHI**2: Gas constant for air divided by the gravitational constant times flow function ($W\sqrt{Tin}/PtAref$) squared

Optimized Output

A description of the output corresponding to sample data set 4 in Appendix "C" is presented in the following paragraph.

The first section of output prints the input values for the variables on input record type 7 as described in section 5.2 of this report. The second section of the printout lists some of the information inputted on record types 1 through 4. The third section, "KNIFE GEOMETRY DATA", lists the geometric parameters associated with each knife of the seal for the maximum number of knives allowed by input. The fourth section lists some information relating to the first optimization iteration. The fifth output section ("KNIFE GEOMETRY DATA") lists knife geometric data for the initial optimization configuration. The resulting calculated flow rate is then printed followed by a table of aerodynamic parameters for each knife station for the configuration being considered. The seventh section lists the optimum value for each seal parameter with the range associated with each (set by input or default). Parameters that are "binding constraints " are flagged. Output sections 4 through 7 are repeated each time the number of seal knives is indexed. The last section of output lists the seal input parameters that are not optimized and summarizes the optimized knife configurations. The optimum seal configuration (i.e. minimum leakage flow) is flagged.

6.0 REFERENCES

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(4) DODGE, LOUIS. "Fluid Throttling Devices", Flow Resistance in Piping and Components, Product Engineering, Reprint R109, McGraw-Hill, New York, New York, March 30, 1964, PP 14-20.

(5) KEARTON, W,J., and T. H. KEH "Leakage of Air Through Labyrinth Glands of Staggered Type", Proceedings of the Institution of Mechanical Engineers, Series A, Vol. 166, No. 2, 1952, PP. 180-188. (Discussion: PP. 189-195.)

(6) HARRISON, Jeffrey, An Investigation of Parameters Influenceing Leakage through Labyrinth Seals with Solid and Honeycomb Lands, (Master's Thesis), Brigham Young University, Provo, Utah, August, 1980.

(7) CAUNCE, D., and P. J. EVERITT, The Leakage of Air Through Stepped Labyrinth Seals, University of Bristol, United Kingdom, June, 1966.

(8) MEYER, C. A., and J. A. LOWRIE, III. The Leakage through Straight and Slant Labyrinths and Honeycomb Seals, (Paper No. 74-WA/PTC-2), Journal of Engineering for Power, Trans. ASME, Series A, Vol. 97, October, 1975, PP. 495-501. (Discussion: PP. 501-502.)

(9) TIPTON, Donald L., Thomas E. SCOTT, and Rodney E. VOGEL, Labyrinth Seal Analysis: Volume III--Analytical and Experimental Development of a Design Model for Labyrinth Seals, AFWAL-TR-85-2103, Allison Gas Turbine Division, General Motors Corporation, Indianapolis, Indiana, January 1986.

7.0 LIST OF SYMBOLS

SYMBOL	DEFINITION	UNITS
A	Cross-sectional area	$in.^2$
A_t	Flow area between the seal knives and land, seal throat	$in.^2$
CL	Clearance between seal knives and land	in.
DTC	Distance-to-contact: axial clearance between knife and land, undefined for constant height straight-through seals	in.
$f(\ )$	Function of the variables ( )	
f	Fanning friction factor	
g_c	Standard gravitational acceleration mass conversion factor	$lb_m ft/lb_b$
H	Seal height	in.
H	Hydraulic diameter, $H = \frac{4A}{P}$	in.
K_c	Contraction coefficient	
K_e	Expansion coefficient	
K_f	Wall friction loss coefficient	
KH	Knife height	in.
KN	Number of knives	
KP	Knife pitch	in.
KR	Knife tip radius	in.
KT	Knife tip thickness	in.
K_{vf}	Venturi-friction coefficient	
$K\beta$	Knife taper angle	deg, °
$K\theta$	Knife slant angle	deg, °
L	Length of the seal	in.
LTSD	Leakage flow direction from the large-to-small seal diameter	
M	Mach number	
P	Wetted perimeter of duct	in.
P_s	Local static pressure	psia
P_D	Seal plenum downstream pressure	psia
P_R	Seal pressure ratio, P_U/P_D	
P_t	Local total pressure	psia

LIST OF SYMBOLS (con't)

SYMBOL	DEFINITION	UNITS
P_U, P_1	Seal plenum upstream pressure	psia
r	P_D/P_U	
R	Gas constant	$\frac{lb_f \; ft}{lb_m \; °R}$
Re	Streamwise Reynolds number, $\frac{\rho VH}{\mu}$	
SH	Step height	in.
STLD	Leakage flow direction from the small-to-large seal diameter	
T	Local total temperature	°F
T_U	Seal upstream plenum temperature	°R
V	Leakage gas velocity	ft/sec
w	Seal airflow rate	lb_m/sec
XMUL	Area correction factor for clearance above a knife which is downstream of a step	
α	jet expansion angle	deg, °
γ	Ratio of specific heats	
δ	jet expansion height	in.
ϵ	Land surface roughness	μ in.
μ	Fluid dynamic viscosity	$\frac{lb_m}{ft \; sec}$
π	Conventional transcendental number, ratio of circular circumference to diameter	
ρ	Density	$\frac{lb_m}{ft^3}$
$\phi = \frac{w\sqrt{T_U}}{P_U A_t}$	Airflow parameter	$\frac{lb_m \; °R^{1/2}}{lb_f \; sec}$

8.0 APPENDIX "A": DESIGN MODEL CORRELATION EQUATIONS

Compressible flow equations applied at the knife throat are:

the isentropic pressure relationship

$$\frac{P_t}{P_s} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

combined with the compressible flow equation of SAINT VENANT-WANTZEL,

$$\phi = \sqrt{\frac{2g_c\gamma}{R(\gamma - 1)}} \left(\frac{P_s}{P_t}\right)^{\frac{1}{\gamma}} \sqrt{1 - \left(\frac{P_s}{P_t}\right)^{\frac{\gamma-1}{\gamma}}}$$

in the form

$$\phi = \sqrt{\frac{g_c\gamma}{R}} \qquad \frac{M}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma + 1}{2(\gamma-1)}}}$$

The drop in total pressure between any two stations in the flow is:

$\Delta P_t = K_c \frac{\gamma}{2} P_s M^2$	contraction loss
$\Delta P_t = K_{vf} \frac{\gamma}{2} P_s M^2$	venturi and friction loss
$\Delta P_t = K_e (P_t - P_s)$	expansion loss

Figure A-1. Basic flow equations used in the Design Model.

K_e = 1.0

K_{vf} = $f(\phi, KT/CL)$

Figure A-3: $0.77 \leq KT/CL \leq 3.3$, but good for $0.0 \leq KT/CL \leq 3.3$
[Derived from Kearton and Keh data for $K_c = 0.70$ (KR very small)]

$$K_{c\ @\ 90°} = 0.7 \left\{ 1. - \mathrm{EXP}\left[C_1 - C_2\, \phi^2 \left(\frac{CL}{KR}\right)^{0.25} + C_3 \left(\frac{KR}{CL}\right) \right] \right\}$$

where

KR - in.	from	Data Source
0.0		KEARTON & KEH (5)
0.00167		Allison
0.005		KOMOTORI & MIYAKE (3)
0.005		HARRISON (6)
0.010		CAUNCE & EVERITT (7)

$K_c = K_{c\ @\ 90°}$ for $K\theta = 90°$

$K_c = K_{c\ @\ 90°} \times [1. - C_4\,(K\theta - 90°)]$ for $K\theta > 90°$ [from IDEL'CHIK (1)]

$K_c = K_{c\ @\ 90°} + C_5\,[1. - \mathrm{SIN}\,(K\theta)]$ for $30° \leq K\theta \leq 90°$
[from Allison plus MEYER AND LOWRIE data (8)]

NOTE: $K\theta$ is actual front surface angle relative to the flow direction so that $K\theta = 90° + K\beta/2$ when the specified knife angle is vertical or beyond, $K\theta \geq 90°$.

C_n = constant, the value of which is given in the program listing for the Design Model, Appendix "D".

Figure A-2. Loss coefficient correlations for a single-knife seal.

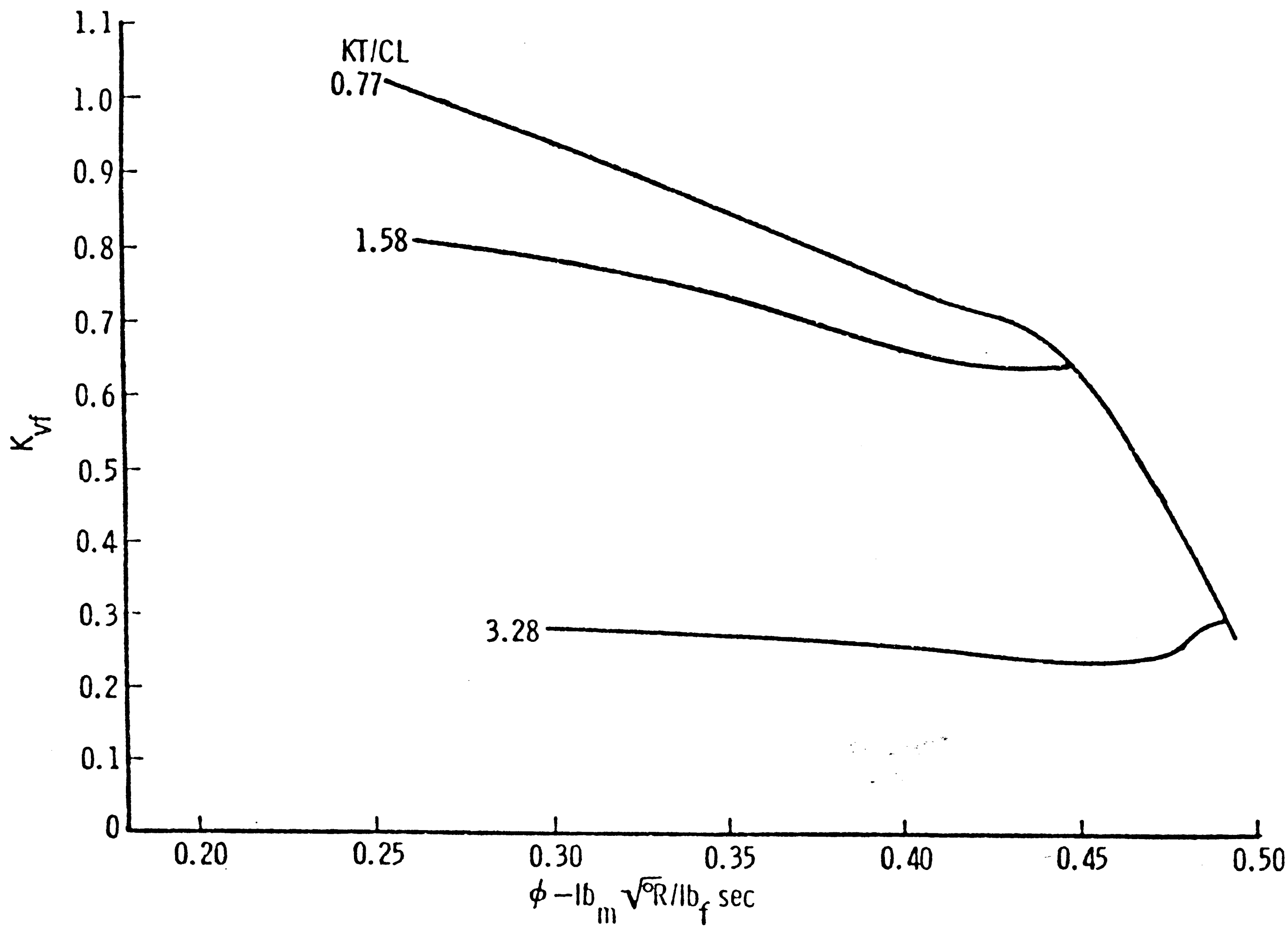
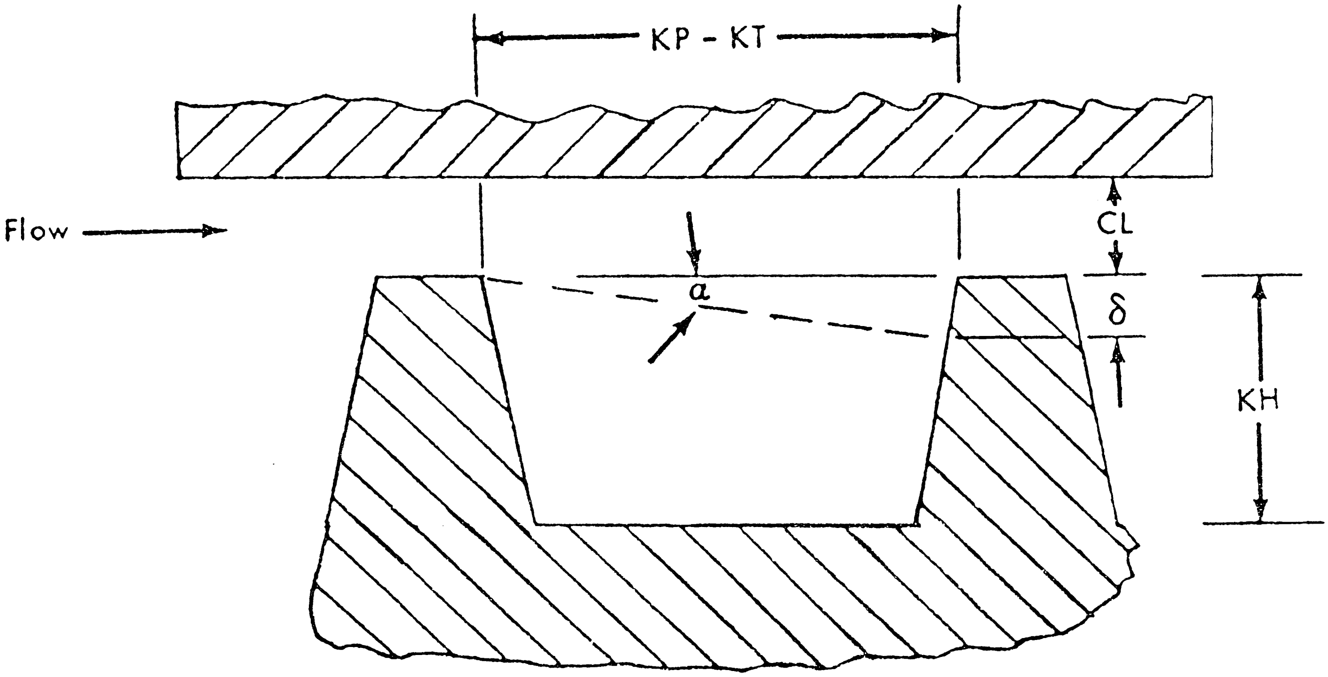


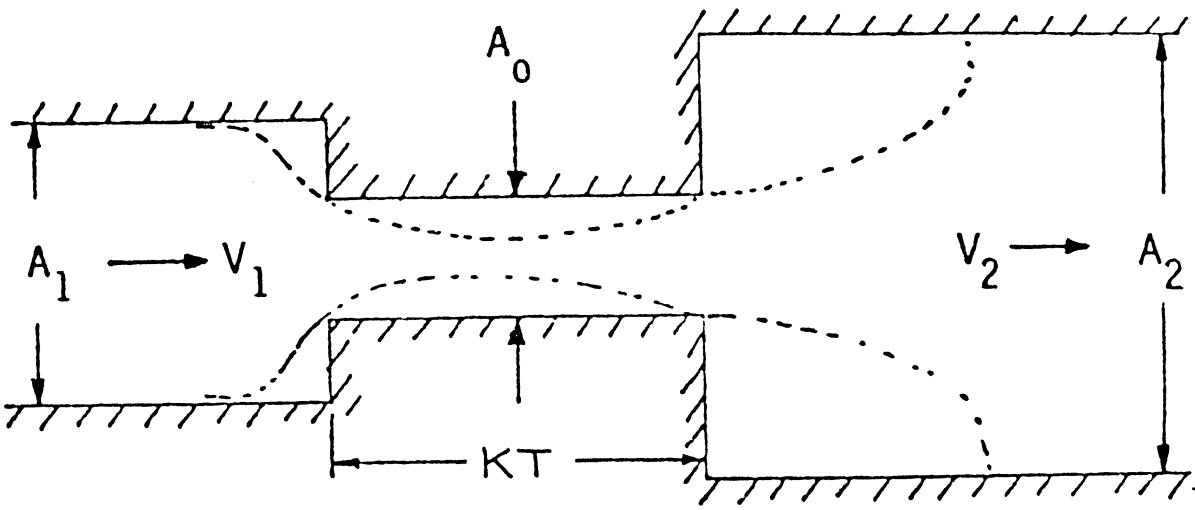
Figure A-3 Venturi-friction coefficient from Kearton and Keh data.



δ = (KP-KT)/[Tan kβ + (1/Tan α)] Kθ = 90 deg

$\delta \approx$ (KP-KT) Tan α α < Kθ < 90 deg

Figure A-4 Schematic of the flow expansion angle for a straight seal.



SUDDEN CONTRACTION

$$K_c = K_c' \left[1 - \frac{A_0}{A_1}\right]$$

VENTURI/FRICTION

$$K_{vf} = K_{vf}' \left[1 - \frac{A_0}{A_1}\right]^{1/2} \left[1 - \frac{A_0}{A_2}\right]$$

SUDDEN EXPANSION

$$K_e = K_e' \left[1 - \frac{A_0}{A_2}\right]^2$$

Figure A-5 Effect of upstream and downstream area on loss coefficient.

JET EXPANSION ANGLE

$$\alpha = C_6\sqrt{\frac{KP-KT}{KH}}$$

for

$$0.54 \leq \frac{(KP-KT)}{KH} \leq 4.0$$

Average deviation = 25%

C_6 = constant. The value of this constant is given in the program listing for the Design Model, Appendix "D".

WALL ROUGHNESS

$$K_{vf} = K_{vf\ smooth}\ (\text{Correction for upstream and downstream knives}) + K_{f\ rough}$$

where

$$K_{f\ rough} = f\ (\varepsilon/H,\ Re,\ KP)$$

$$A_t = A_{t\ smooth}\left(\frac{CL + \varepsilon}{CL}\right)$$

Figure A-6. Straight seal correlations in the Design Model.

STEPPED SEAL AREA MULTIPLIER, XMUL

STLD Flow Direction

$$XMUL = C_7 \, (DTC/CL) \, (KT/CL)^{C_8} \, (DTC/(KP-KT))^{C_9} \, (KH/CL)^{C_{10}} \ldots$$

$$\ldots \, ((KP-KT)/KH)^{C_{11}} \, (SH/CL)^{C_{12}} \Big/ \sqrt{(DTC/CL)^2 + C_{13}}$$

$0.85 \le DTC/CL \le 40$, $0.21 \le KT/CL \le 2.6$, $0.09 \le DTC/(KP-KT) \le 1.0$,

$5.1 \le KH/CL \le 19.4$, $1.16 \le (KP-KT)/KH \le 1.76$, $2.0 \le SH/CL \le 29.4$

LTSD Flow Direction

$$XMUL = XMUL_{STLD} \quad C_{14} \quad (KH/CL)^{C_{15}}$$

$4.0 \le DTC/CL \le 19.4$, $0.50 \le KT/CL \le 1.5$, $0.35 \le DTC/(KP-KT) \le 0.50$

$5.1 \le KH/CL \le 28$, $1.02 \le (KP-KT)/KH \le 1.9$, $4.0 \le SH/CL \le 12.5$

Note: The limits on the seal parameters result from the range of the seal geometries used in developing the correlation equations.

WALL ROUGHNESS

$$K_{vf} = K'_{vf} + K_{f\ rough}$$

$$K_{f\ rough} = f(\varepsilon/H,\ Re,\ KT)$$

$$A_t = A_{t\ smooth} \left(\frac{CL + \varepsilon}{CL} \right)$$

Figure A-7. Stepped seal correlations in the Design Model.

Appendix B: Sample Input Data

Sample dataset 1 is for a straight labyrinth seal:

```
    0     1     1     0     1 1.3600e+000 2.8970e+001
\CFD\OUTPUT\KTK\dataset1
Straight Labyrinth Seal
Data set #1
    5     1STRAI
 3.5000e+001 0.0000e+000 2.6000e+000 0.0000e+000  0.001  0.000  0.000
 5.0000e-003 1.7000e+000 1.0000e-002 4.0000e-002 3.0000e-002 0.0000e+000
 0.0000e+000 90.000 20.000 0.0000e+000 0.0000e+000900.000
    0     0  0.000
```

Sample dataset 2 is for a mixed labyrinth seal:

```
    0     1     1     0     1 1.3600e+000 2.8970e+001
\CFD\OUTPUT\KTK\dataset2
Mixed Labyrinth Seal
Data set #2
    4     4MIXED
 3.5000e+001 0.0000e+000 0.0000e+000 0.0000e+000  0.001  0.000  0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 1.9000e-001 0.0000e+000
 1.6000e-001 90.000 20.000 3.1000e+000 5.0000e+001900.000
    0     0  0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 1.9000e-001 0.0000e+000
 1.6000e-001 90.000 20.000 3.1000e+000 5.0000e+001900.000
    0     0  0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 1.9000e-001 8.0000e-002
 1.7000e-001 90.000 20.000 2.9400e+000 5.0000e+001900.000
    0     0  0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 1.9000e-001 8.0000e-002
 1.6000e-001 90.000 20.000 2.8000e+000 5.0000e+001900.000
    0     0  0.000
```

Sample dataset 3 is for a stepped labyrinth seal:

```
    0     1     1     0     1 1.3600e+000 2.8970e+001
\CFD\OUTPUT\KTK\dataset3
Stepped Labyrinth Seal
Data set #3
    4     4STEP LTSD
 3.5000e+001 0.0000e+000 0.0000e+000 0.0000e+000  0.001   0.000   0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 8.0000e-002 5.0000e-002
 3.4000e-001 90.000 20.000 3.3200e+000 5.0000e+001900.000
    0     0  0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 8.0000e-002 5.0000e-002
 1.6000e-001 90.000 20.000 3.2200e+000 5.0000e+001900.000
    0     0  0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 8.0000e-002 5.0000e-002
 1.6000e-001 90.000 20.000 3.1200e+000 5.0000e+001900.000
    0     0  0.000
 9.0000e-003 1.7000e+000 1.0000e-002 1.6000e-001 8.0000e-002 5.0000e-002
 1.6000e-001 90.000 20.000 3.0200e+000 5.0000e+001900.000
    0     0  0.000
```

Sample dataset 4 is for an optimized straight labyrinth seal:

```
    0     1     1     0     1 1.3600e+000 2.8970e+001
\CFD\OUTPUT\KTK\dataset4
Straight Labyrinth Seal Optimization
Data set #4
    5     1STRAI      UNITYOPTIM
 3.5000e+001 0.0000e+000 2.6000e+000 0.0000e+000  0.001   0.000   1.079
 8.0000e-003 1.7000e+000 1.0000e-002 1.0000e-001 8.0000e-002 0.0000e+000
 0.0000e+000 90.000 20.000 0.0000e+000 0.0000e+000900.000
    0     0  0.000
 5.0000e-001 2.5000e-001STRAI          0     0     0
KT                    9.0000e-003 2.0000e-002
KP                    3.5000e-001 6.0000e-001
KTHETA                4.5000e+001 9.0000e+001
ROUGH                 3.0000e+001 3.0000e+001
KN                    6.0000e+000 6.0000e+000
END
```

Appendix C: Sample Output Data

The program outputs listed on the following pages was generated from the datasets listed in Appendix B.

F L O W   R E S U L T S   A T   C H O K E   P O I N T   (W = 0.01814 LB/SEC   ITERATIONS = 25)

STN NO.	KNIFE NO.	AREA (IN**2)	TEMP (DEG R)	WRT/PTA	WRT/PSA	4FL/D	KFACT	LOSS TYPE	PT (PSIA)	PS (PSIA)	MN	KFACT METHOD	PARM	AMUL	ADDER	XKUNC	MOD AREA (IN**2)
1		0.041	900.00	0.3799	0.4426				35.000	30.040	0.479						0.041
2	1	0.041	900.00	0.3979	0.4731	0.000	0.337	CONTR	33.419	28.104	0.511	Q	0.340	0.860	0.000	0.392	0.041
3	1	0.041	900.00	0.4081	0.4916	0.000	0.169	LHOLE	32.577	27.047	0.530	Q	2.000	0.282	0.000	0.599	0.041
4	1	0.041	900.00	0.4137	0.5020	0.000	0.080	EXPND	32.137	26.484	0.540	PT-PS	0.000	0.080	0.000	1.000	0.041
5	2	0.041	900.00	0.4211	0.5162	0.000	0.106	CONTR	31.578	25.759	0.555	Q	0.340	0.243	0.000	0.438	0.041
6	2	0.041	900.00	0.4274	0.5288	0.000	0.087	LHOLE	31.111	25.142	0.568	Q	2.000	0.150	0.000	0.579	0.041
7	2	0.041	900.00	0.4340	0.5426	0.000	0.080	EXPND	30.636	24.504	0.582	PT-PS	0.000	0.080	0.000	1.000	0.041
8	3	0.041	900.00	0.4432	0.5627	0.000	0.113	CONTR	30.001	23.631	0.602	Q	0.340	0.243	0.000	0.464	0.041
9	3	0.041	900.00	0.4506	0.5799	0.000	0.085	LHOLE	29.505	22.929	0.619	Q	2.000	0.150	0.000	0.569	0.041
10	3	0.041	900.00	0.4588	0.5998	0.000	0.080	EXPND	28.982	22.166	0.639	PT-PS	0.000	0.080	0.000	1.000	0.041
11	4	0.041	900.00	0.4708	0.6319	0.000	0.120	CONTR	28.244	21.041	0.671	Q	0.340	0.243	0.000	0.494	0.041
12	4	0.041	900.00	0.4782	0.6538	0.000	0.068	LHOLE	27.807	20.337	0.693	Q	2.000	0.150	0.000	0.453	0.041
13	4	0.041	900.00	0.4886	0.6883	0.000	0.080	EXPND	27.213	19.319	0.726	PT-PS	0.000	0.080	0.000	1.000	0.041
14	5	0.041	900.00	0.5050	0.7559	0.000	0.128	CONTR	26.329	17.589	0.791	Q	0.340	0.243	0.000	0.526	0.041
15	5	0.041	900.00	0.5265	0.9831	0.000	0.143	LHOLE	25.255	13.525	0.999	Q	2.000	0.531	0.000	0.270	0.041
16	5	0.041	900.00	0.9831		0.000	1.000	EXPND	13.525			PT-PS	0.000	1.000	0.000	1.000	0.041

F L O W   C U R V E   WHERE PR = PT UP / PT DOWN AND PHI = W * SQRT(TIN) / (PT UP * AREF)   (WHERE AREF= 0.041)

I	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.-1./PR**2	0.00000	0.00668	0.03179	0.07401	0.13162	0.20284	0.28461	0.37238	0.46286	0.55390	0.64517	0.73033	0.78207	0.85068
PHI**2	0.00000	0.00175	0.00831	0.01870	0.03188	0.04689	0.06287	0.07903	0.09469	0.10923	0.12215	0.13300	0.14145	0.14432
R/G * PHI**2	0.00000	0.00290	0.01378	0.03101	0.05285	0.07774	0.10422	0.13102	0.15698	0.18110	0.20251	0.22051	0.23450	0.23927

```
K N I F E -- T O -- K N I F E   S E A L   D E S I G N   M O D E L

Mixed Labyrinth Seal
Data set #2
                  I N P U T   D A T A   R A N G E   C H E C K
KNIFE  1
         VARIABLE        MIN      VALUE     MAX
            THETA        30.       90.0     90.
            KT/CL        0.0      1.111     3.3
         (E-30)/D        0.0     1111.1  27000.
KNIFE  2
         VARIABLE        MIN      VALUE     MAX
            THETA        30.       90.0     90.
            KT/CL        0.0      1.111     3.3
       (KP-KT)/KH       0.54      0.789      4.
         (E-30)/D        0.0     1111.1  27000.
KNIFE  3
         VARIABLE        MIN      VALUE     MAX
            THETA        30.       90.0     90.
            KT/CL       0.21      1.111     2.6
            KH/CL        5.1     21.111    29.4
     DTC/(KP-KT)        0.09      1.133     1.0 ****
           DTC/CL       0.85     18.889    40.0
       (KP-KT)/KH **** 1.16      0.789    1.76
            SH/CL       2.02      8.889    29.4
         (E-30)/D        0.0     1111.1  27000.
KNIFE  4
         VARIABLE        MIN      VALUE     MAX
            THETA        30.       90.0     90.
            KT/CL       0.21      1.111     2.6
            KH/CL        5.1     21.111    29.4
     DTC/(KP-KT)        0.09      1.067     1.0 ****
           DTC/CL       0.85     17.778    40.0
       (KP-KT)/KH **** 1.16      0.789    1.76
            SH/CL       2.02      8.889    29.4
         (E-30)/D        0.0     1111.1  27000.
     ----------------------------------------------------
     W A R N I N G   SEAL CALCULATION MAY BE IN ERROR
     **** INDICATES VARIABLES OUTSIDE RANGE OF DATA BASE
     USED FOR EMPIRICAL CORRELATION
     ----------------------------------------------------
```

K N I F E -- T O -- K N I F E   S E A L   D E S I G N   M O D E L

Mixed Labyrinth Seal
Data set #2

```
SPECIFIC HEAT RATIO    (GAMMA)  =    1.3600
MOLECULAR WEIGHT                =   28.9700
NUMBER OF KNIVES                =         4
SEAL TYPE                       =     MIXED
FLOW DIRECTION                  =
SEAL LENGTH (2-D SEAL)          =    0.0000 (INCHES)
AVG. KNIFE DIAMETER (3-D SEAL)  =    2.9850 (INCHES)
INLET TOTAL PRESSURE            =   35.0000 (PSIA)
```

K N I F E   G E O M E T R Y   D A T A

KNIFE NO.	CL (IN)	KR (IN)	KT (IN)	KP (IN)	KH (IN)	SH (IN)	DTC (IN)	THETA (DEG)	BETA (DEG)	DIA (IN)	ROUGH (RMS)	TEMP (DEGR)	KCCO	KECO	4FL/D	DEL C (IN)	DEL E (IN)	AREA MULT	ALPHA (DEG)
1	0.0090	0.00170	0.0100	0.1600	0.1900	0.0000	0.1600	90.0	20.0	3.1000	50.00	900.0	-1	0	0.00	0.0000	0.0087	1.000	
2	0.0090	0.00170	0.0100	0.1600	0.1900	0.0000	0.1600	90.0	20.0	3.1000	50.00	900.0	1	-1	0.00	0.0087	0.0000	1.000	3.368
3	0.0090	0.00170	0.0100	0.1600	0.1900	0.0800	0.1700	90.0	20.0	2.9400	50.00	900.0	-1	-1	0.00	0.0000	0.0000	1.088	3.368
4	0.0090	0.00170	0.0100	0.1600	0.1900	0.0800	0.1600	90.0	20.0	2.8000	50.00	900.0	-1	-1	0.00	0.0000	0.0000	1.081	3.368

F L O W   R E S U L T S   A T   C H O K E   P O I N T   (W = 0.02728 LB/SEC   ITERATIONS = 25)

STN NO.	KNIFE NO.	AREA (IN**2)	TEMP (DEG R)	WRT/PTA	WRT/PSA	4FL/D	KFACT	LOSS TYPE	PT (PSIA)	PS (PSIA)	MN	KFACT METHOD	PARM	AMUL	ADDER	XKUNC	MOD AREA (IN**2)
1		0.088	900.00	0.2646	0.2821				35.000	32.820	0.309						0.088
2	1	0.088	900.00	0.2691	0.2876	0.000	0.275	CONTR	34.415	32.191	0.315	Q	0.189	0.860	0.000	0.320	0.088
3	1	0.088	900.00	0.2781	0.2988	0.000	0.516	LHOLE	33.295	30.983	0.327	Q	1.111	0.493	0.060	0.927	0.088
4	1	0.088	900.00	0.2829	0.3048	0.000	0.243	EXPND	32.734	30.376	0.333	PT-PS	0.000	0.243	0.000	1.000	0.088
5	2	0.088	900.00	0.2858	0.3085	0.000	0.146	CONTR	32.398	30.011	0.337	Q	0.189	0.424	0.000	0.345	0.088
6	2	0.088	900.00	0.2995	0.3262	0.000	0.639	LHOLE	30.916	28.389	0.356	Q	1.111	0.702	0.004	0.905	0.088
7	2	0.088	900.00	0.3262	0.3592	0.000	1.000	EXPND	28.389	25.776	0.379	PT-PS	0.000	1.000	0.000	1.000	0.088
8	3	0.083	900.00	0.3256	0.3613	0.000	0.336	CONTR	27.541	24.825	0.393	Q	0.189	0.860	0.000	0.391	0.091
9	3	0.083	900.00	0.3543	0.4025	0.000	0.851	LHOLE	25.317	22.283	0.437	Q	1.111	1.000	0.004	0.847	0.091
10	3	0.083	900.00	0.4025	0.4965	0.000	1.000	EXPND	22.283	18.062	0.564	PT-PS	0.000	1.000	0.000	1.000	0.091
11	4	0.079	900.00	0.4619	0.6078	0.000	0.451	CONTR	20.523	15.597	0.647	Q	0.189	0.860	0.000	0.525	0.086
12	4	0.079	900.00	0.5265	0.9838	0.000	0.567	LHOLE	18.005	9.635	1.000	Q	1.111	1.000	0.004	0.563	0.086
13	4	0.079	900.00	0.9838		0.000	1.000	EXPND	9.635			PT-PS	0.000	1.000	0.000	1.000	0.086

F L O W   C U R V E   WHERE PR = PT UP / PT DOWN AND PHI = W * SQRT(TIN) / (PT UP * AREF)   (WHERE AREF= 0.085)

I	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.-1./PR**2	0.00000	0.00971	0.04622	0.10448	0.17955	0.26697	0.36263	0.46260	0.56129	0.65488	0.73990	0.81563	0.88987	0.92421
PHI**2	0.00000	0.00092	0.00440	0.00989	0.01686	0.02479	0.03324	0.04179	0.05007	0.05776	0.06459	0.07033	0.07479	0.07631
R/G * PHI**2	0.00000	0.00153	0.00729	0.01640	0.02795	0.04110	0.05511	0.06928	0.08300	0.09576	0.10708	0.11659	0.12399	0.12651

```
K N I F E -- T O -- K N I F E   S E A L   D E S I G N   M O D E L

Stepped Labyrinth Seal
Data set #3
               I N P U T   D A T A   R A N G E   C H E C K
KNIFE  1
          VARIABLE       MIN      VALUE      MAX
             THETA       30.       90.0      90.
             KT/CL      0.50      1.111      1.5
             KH/CL       5.1      8.889     28.0
      DTC/(KP-KT)       0.35      2.267      0.5 ****
           DTC/CL       4.10     37.778     19.4 ****
        (KP-KT)/KH      1.02      1.875     1.90
             SH/CL      4.00      5.556     12.5
          (E-30)/D       0.0     1111.1   27000.
KNIFE  2
          VARIABLE       MIN      VALUE      MAX
             THETA       30.       90.0      90.
             KT/CL      0.50      1.111      1.5
             KH/CL       5.1      8.889     28.0
      DTC/(KP-KT)       0.35      1.067      0.5 ****
           DTC/CL       4.10     17.778     19.4
        (KP-KT)/KH      1.02      1.875     1.90
             SH/CL      4.00      5.556     12.5
          (E-30)/D       0.0     1111.1   27000.
KNIFE  3
          VARIABLE       MIN      VALUE      MAX
             THETA       30.       90.0      90.
             KT/CL      0.50      1.111      1.5
             KH/CL       5.1      8.889     28.0
      DTC/(KP-KT)       0.35      1.067      0.5 ****
           DTC/CL       4.10     17.778     19.4
        (KP-KT)/KH      1.02      1.875     1.90
             SH/CL      4.00      5.556     12.5
          (E-30)/D       0.0     1111.1   27000.
KNIFE  4
          VARIABLE       MIN      VALUE      MAX
             THETA       30.       90.0      90.
             KT/CL      0.50      1.111      1.5
             KH/CL       5.1      8.889     28.0
      DTC/(KP-KT)       0.35      1.067      0.5 ****
           DTC/CL       4.10     17.778     19.4
        (KP-KT)/KH      1.02      1.875     1.90
             SH/CL      4.00      5.556     12.5
          (E-30)/D       0.0     1111.1   27000.
      ----------------------------------------------------
      W A R N I N G   SEAL CALCULATION MAY BE IN ERROR
      **** INDICATES VARIABLES OUTSIDE RANGE OF DATA BASE
      USED FOR EMPIRICAL CORRELATION
      ----------------------------------------------------
```

K N I F E -- T O -- K N I F E   S E A L   D E S I G N   M O D E L

Stepped Labyrinth Seal
Data set #3

SPECIFIC HEAT RATIO (GAMMA)	=	1.3600
MOLECULAR WEIGHT	=	28.9700
NUMBER OF KNIVES	=	4
SEAL TYPE	=	STEPPED
FLOW DIRECTION	=	LTSD
SEAL LENGTH (2-D SEAL)	=	0.0000 (INCHES)
AVG. KNIFE DIAMETER (3-D SEAL)	=	3.1700 (INCHES)
INLET TOTAL PRESSURE	=	35.0000 (PSIA)

K N I F E   G E O M E T R Y   D A T A

KNIFE NO.	CL (IN)	KR (IN)	KT (IN)	KP (IN)	KH (IN)	SH (IN)	DTC (IN)	THETA (DEG)	BETA (DEG)	DIA (IN)	ROUGH (RMS)	TEMP (DEGR)	KCCO	KECO	4FL/D	DEL C (IN)	DEL E (IN)	AREA MULT	ALPHA (DEG)
1	0.0090	0.00170	0.0100	0.1600	0.0800	0.0500	0.3400	90.0	20.0	3.3200	50.00	900.0	-1	-1	0.00	0.0000	0.0000	1.320	
2	0.0090	0.00170	0.0100	0.1600	0.0800	0.0500	0.1600	90.0	20.0	3.2200	50.00	900.0	-1	-1	0.00	0.0000	0.0000	1.216	0.000
3	0.0090	0.00170	0.0100	0.1600	0.0800	0.0500	0.1600	90.0	20.0	3.1200	50.00	900.0	-1	-1	0.00	0.0000	0.0000	1.216	0.000
4	0.0090	0.00170	0.0100	0.1600	0.0800	0.0500	0.1600	90.0	20.0	3.0200	50.00	900.0	-1	-1	0.00	0.0000	0.0000	1.216	0.000

F L O W   R E S U L T S   A T   C H O K E   P O I N T   (W = 0.03146 LB/SEC   ITERATIONS = 25)

STN NO.	KNIFE NO.	AREA (IN**2)	TEMP (DEG R)	WRT/PTA	WRT/PSA	4FL/D	KFACT	LOSS TYPE	PT (PSIA)	PS (PSIA)	MN	KFACT METHOD	PARM	AMUL	ADDER	XKUNC	MOD AREA (IN**2)
1		0.094	900.00	0.2158	0.2249				35.000	33.586	0.247						0.125
2	1	0.094	900.00	0.2177	0.2270	0.000	0.217	CONTR	34.698	33.270	0.249	Q	0.189	0.860	0.000	0.252	0.125
3	1	0.094	900.00	0.2266	0.2372	0.000	0.973	LHOLE	33.331	31.839	0.260	Q	1.111	1.000	0.003	0.969	0.125
4	1	0.094	900.00	0.2372	0.2531	0.000	1.000	EXPND	31.839	29.837	0.310	PT-PS	0.000	1.000	0.000	1.000	0.125
5	2	0.091	900.00	0.2703	0.2891	0.000	0.276	CONTR	31.299	29.257	0.316	Q	0.189	0.860	0.000	0.321	0.112
6	2	0.091	900.00	0.2872	0.3103	0.000	0.929	LHOLE	29.449	27.255	0.339	Q	1.111	1.000	0.004	0.925	0.112
7	2	0.091	900.00	0.3103	0.3429	0.000	1.000	EXPND	27.255	24.667	0.386	PT-PS	0.000	1.000	0.000	1.000	0.112
8	3	0.088	900.00	0.3306	0.3682	0.000	0.341	CONTR	26.404	23.709	0.401	Q	0.189	0.860	0.000	0.397	0.108
9	3	0.088	900.00	0.3604	0.4118	0.000	0.843	LHOLE	24.220	21.197	0.447	Q	1.111	1.000	0.004	0.840	0.108
10	3	0.088	900.00	0.4118	0.5080	0.000	1.000	EXPND	21.197	17.182	0.564	PT-PS	0.000	1.000	0.000	1.000	0.108
11	4	0.086	900.00	0.4619	0.6078	0.000	0.451	CONTR	19.523	14.835	0.647	Q	0.189	0.860	0.000	0.525	0.105
12	4	0.086	900.00	0.5265	0.9833	0.000	0.567	LHOLE	17.127	9.170	1.000	Q	1.111	1.000	0.004	0.563	0.105
13	4	0.086	900.00	0.9833		0.000	1.000	EXPND	9.170			PT-PS	0.000	1.000	0.000	1.000	0.105

F L O W   C U R V E   WHERE PR = PT UP / PT DOWN AND PHI = W * SQRT(TIN) / (PT UP * AREF)   (WHERE AREF= 0.090)

I	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.-1./PR**2	0.00000	0.01005	0.04774	0.10763	0.18440	0.27332	0.37008	0.47068	0.57013	0.66397	0.74923	0.82473	0.89696	0.93135
PHI**2	0.00000	0.00109	0.00519	0.01167	0.01989	0.02925	0.03921	0.04930	0.05906	0.06814	0.07620	0.08297	0.08823	0.09002
R/G * PHI**2	0.00000	0.00181	0.00860	0.01934	0.03297	0.04849	0.06501	0.08173	0.09792	0.11297	0.12633	0.13755	0.14628	0.14925

K N I F E -- T O -- K N I F E   S E A L   D E S I G N   M O D E L

Straight Labyrinth Seal Optimization
Data set #4
LMAX 0.500000   HMAX 0.250000   PRATIO 1.07900   TYPE STRAI   DIRECTION   ISRCHP 0   IPASSP 0   IWPRNT 0

INITIAL VALUES TO BEGIN OPTIMIZATION

SPECIFIC HEAT RATIO	(GAMMA)	=	1.3600	
MOLECULAR WEIGHT		=	28.9700	
)MAX NUMBER OF KNIVES		=	6	
SEAL TYPE		=	STRAIGHT	
FLOW DIRECTION		=		
SEAL LENGTH (2-D SEAL)		=	0.0000	(INCHES)
AVG. KNIFE DIAMETER (3-D SEAL)		=	2.6000	(INCHES)
FLOW DIVERGENCE ANGLE	(ALPHA)	=	0.0000	(DEGREES)
INLET TOTAL PRESSURE		=	35.0000	(PSIA)

K N I F E   G E O M E T R Y   D A T A

KNIFE NO.	CL (IN)	KR (IN)	KT (IN)	KP (IN)	KH (IN)	SH (IN)	DTC (IN)	THETA (DEG)	BETA (DEG)	DIA (IN)	ROUGH (RMS)	TEMP (DEGR)
1	0.0080	0.00170	0.0100	0.1000	0.1020	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0
2	0.0080	0.00170	0.0100	0.1000	0.1020	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0
3	0.0080	0.00170	0.0100	0.1000	0.1020	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0
4	0.0080	0.00170	0.0100	0.1000	0.1020	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0
5	0.0080	0.00170	0.0100	0.1000	0.1020	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0
6	0.0080	0.00170	0.0100	0.1000	0.1020	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0

)PTIMIZATION STEP FOR STRAIGHT SEAL WITH NO. KNIVES = 6

RANGES AVAILABLE FROM EMPIRICAL DATA

	MIN	INITIAL	MAX	
1	0.900000E-02	0.100000E-01	0.200000E-01	KT
2	0.350000	0.960400E-01	0.980000E-01	KP
3	1.00000	1.00000	1.00000	KH/KP
4	0.100000E-01	0.000000E+00	1.00000	SH
5	45.0000	89.0000	90.0000	KTHETA
6	30.0000	30.0000	30.0000	ROUGH
7	0.100000E-02		3.30000	KT/CL
8	0.540000		4.00000	(KP-KT)/KH/CL

K N I F E -- T O -- K N I F E   S E A L   D E S I G N   M O D E L

Straight Labyrinth Seal
Data set #1

```
SPECIFIC HEAT RATIO   (GAMMA)    =    1.3600
MOLECULAR WEIGHT                 =   28.9700
NUMBER OF KNIVES                 =         5
SEAL TYPE                        =  STRAIGHT
FLOW DIRECTION                   =
SEAL LENGTH (2-D SEAL)           =    0.0000 (INCHES)
AVG. KNIFE DIAMETER (3-D SEAL)   =    2.6000 (INCHES)
INLET TOTAL PRESSURE             =   35.0000 (PSIA)
```

K N I F E   G E O M E T R Y   D A T A

KNIFE NO.	CL (IN)	KR (IN)	KT (IN)	KP (IN)	KH (IN)	SH (IN)	DTC (IN)	THETA (DEG)	BETA (DEG)	DIA (IN)	ROUGH (RMS)	TEMP (DEGR)	KCCO	KECO	4FL/D	DEL C (IN)	DEL E (IN)	AREA MULT	ALPHA (DEG)
1	0.0050	0.00170	0.0100	0.0400	0.0300	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0	-1	1	0.00	0.0000	0.0020	1.000	
2	0.0050	0.00170	0.0100	0.0400	0.0300	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0	1	1	0.00	0.0020	0.0020	1.000	3.790
3	0.0050	0.00170	0.0100	0.0400	0.0300	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0	1	1	0.00	0.0020	0.0020	1.000	3.790
4	0.0050	0.00170	0.0100	0.0400	0.0300	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0	1	1	0.00	0.0020	0.0020	1.000	3.790
5	0.0050	0.00170	0.0100	0.0400	0.0300	0.0000	0.0000	90.0	20.0	2.6000	0.00	900.0	1	-1	0.00	0.0020	0.0000	1.000	3.790

I N P U T   D A T A   R A N G E   C H E C K

ALL KNIVES

VARIABLE	MIN	VALUE	MAX
THETA	30.	90.0	90.
KT/CL	0.0	2.000	3.3
(KP-KT)/KH	0.54	1.000	4.

N O R M A L   C O N V E R G E N C E

RESULTS FOR CONVERGED VARIABLE VALUES

NUMBER OF KNIVES	=	6
SEAL TYPE	=	STRAIGHT
FLOW DIRECTION	=	STLD
SEAL LENGTH (2-D SEAL)	=	0.0000 (INCHES)
AVG. KNIFE DIAMETER (3-D SEAL)	=	2.6000 (INCHES)
INLET TOTAL PRESSURE	=	35.0000 (PSIA)
AREA NORMALIZING FACTOR	=	1.0000

K N I F E   G E O M E T R Y   D A T A

KNIFE NO.	CL (IN)	KR (IN)	KT (IN)	KP (IN)	KH (IN)	SH (IN)	DTC (IN)	THETA (DEG)	BETA (DEG)	DIA (IN)	ROUGH (RMS)	TEMP (DEGR)	KCCO	KECO	4FL/D	DEL C (IN)	DEL E (IN)	AREA MULT	ALPHA (DEG)
1	0.0080	0.00170	0.0090	0.0960	0.0960	0.0000	0.0000	45.0	20.0	2.6000	30.00	900.0	-1	1	0.00	0.0000	0.0055	1.000	
2	0.0080	0.00170	0.0090	0.0960	0.0960	0.0000	0.0000	45.0	20.0	2.6000	30.00	900.0	1	1	0.00	0.0055	0.0055	1.000	3.608
3	0.0080	0.00170	0.0090	0.0960	0.0960	0.0000	0.0000	45.0	20.0	2.6000	30.00	900.0	1	1	0.00	0.0055	0.0055	1.000	3.608
4	0.0080	0.00170	0.0090	0.0960	0.0960	0.0000	0.0000	45.0	20.0	2.6000	30.00	900.0	1	1	0.00	0.0055	0.0055	1.000	3.608
5	0.0080	0.00170	0.0090	0.0960	0.0960	0.0000	0.0000	45.0	20.0	2.6000	30.00	900.0	1	1	0.00	0.0055	0.0055	1.000	3.608
6	0.0080	0.00170	0.0090	0.0960	0.0960	0.0000	0.0000	45.0	20.0	2.6000	30.00	900.0	1	-1	0.00	0.0055	0.0000	1.000	3.608

FLOW 0.856995E-02   PRESSURE RATIO 1.07900   DESIRED PR 1.07900

F L O W   R E S U L T S   A T   S P E C I F I E D   F L O W   R A T E   (W = 0.00857 LB/SEC   ITERATIONS = 45)

STN NO.	KNIFE NO.	AREA (IN**2)	TEMP (DEG R)	WRT/PTA	WRT/PSA	4FL/D	KFACT	LOSS TYPE	PT (PSIA)	PS (PSIA)	MN	KFACT METHOD	PARM	AMUL	ADDER	XKUNC	MOD AREA (IN**2)
1		0.066	900.00	0.1121	0.1133				35.000	34.631	0.125						0.066
2	1	0.066	900.00	0.1132	0.1144	0.000	0.914	CONTR	34.664	34.292	0.126	Q	0.213	1.000	0.798	0.116	0.066
3	1	0.066	900.00	0.1137	0.1149	0.000	0.415	LHOLE	34.510	34.136	0.127	Q	1.126	0.407	0.000	1.021	0.066
4	1	0.066	900.00	0.1139	0.1151	0.000	0.166	EXPND	34.448	34.074	0.127	PT-PS	0.000	0.166	0.000	1.000	0.066
5	2	0.066	900.00	0.1143	0.1156	0.000	0.372	CONTR	34.309	33.933	0.127	Q	0.213	0.407	0.798	0.117	0.066
6	2	0.066	900.00	0.1147	0.1159	0.000	0.265	LHOLE	34.210	33.833	0.128	Q	1.126	0.260	0.000	1.021	0.066
7	2	0.066	900.00	0.1149	0.1162	0.000	0.166	EXPND	34.148	33.770	0.128	PT-PS	0.000	0.166	0.000	1.000	0.066
8	3	0.066	900.00	0.1153	0.1166	0.000	0.373	CONTR	34.007	33.628	0.129	Q	0.213	0.407	0.798	0.118	0.066
9	3	0.066	900.00	0.1157	0.1170	0.000	0.265	LHOLE	33.907	33.526	0.129	Q	1.126	0.260	0.000	1.020	0.066
10	3	0.066	900.00	0.1159	0.1172	0.000	0.166	EXPND	33.844	33.463	0.129	PT-PS	0.000	0.166	0.000	1.000	0.066
11	4	0.066	900.00	0.1164	0.1177	0.000	0.373	CONTR	33.702	33.319	0.130	Q	0.213	0.407	0.798	0.119	0.066
12	4	0.066	900.00	0.1167	0.1181	0.000	0.265	LHOLE	33.601	33.217	0.130	Q	1.126	0.260	0.000	1.019	0.066
13	4	0.066	900.00	0.1170	0.1183	0.000	0.166	EXPND	33.538	33.153	0.130	PT-PS	0.000	0.166	0.000	1.000	0.066
14	5	0.066	900.00	0.1175	0.1188	0.000	0.374	CONTR	33.395	33.008	0.131	Q	0.213	0.407	0.798	0.120	0.066
15	5	0.066	900.00	0.1178	0.1192	0.000	0.264	LHOLE	33.293	32.905	0.131	Q	1.126	0.260	0.000	1.019	0.066
16	5	0.066	900.00	0.1180	0.1194	0.000	0.166	EXPND	33.228	32.840	0.132	PT-PS	0.000	0.166	0.000	1.000	0.066
17	6	0.066	900.00	0.1186	0.1200	0.000	0.374	CONTR	33.084	32.693	0.132	Q	0.213	0.407	0.798	0.121	0.066
18	6	0.066	900.00	0.1195	0.1209	0.000	0.650	LHOLE	32.831	32.437	0.133	Q	1.126	0.638	0.000	1.018	0.066
19	6	0.066	900.00	0.1209		0.000	1.000	EXPND	32.437			PT-PS	0.000	1.000	0.000	1.000	0.066

PARAMETER VALUES AND DERIVATIVES FOR STRAIGHT SEAL 6 KNIVES MIN FLOW 0.856995E-02

	MIN	OPTIMUM	MAX	DEL W/DEL X
* KT	0.900000E-02	0.900896E-02	0.200000E-01	436.632
KP	0.350000	0.960400E-01	0.980000E-01	0.000000E+00
KH/KP	1.00000	1.00000	1.00000	0.000000E+00
SH	0.100000E-01	0.000000E+00	1.00000	0.000000E+00
* KTHETA	45.0000	45.0444	90.0000	0.317253
ROUGH	30.0000	30.0000	30.0000	0.000000E+00

CONSTRAINTS

	MIN	VALUE	MAX
KT/CL	0.100000E-02	1.12612	3.30000
(KP-KT)/KH	0.540000	0.906196	4.00000

* INDICATES BINDING CONSTRAINTS

Straight Labyrinth Seal Optimization
Data set #4

CLEARANCE	0.800000E-02
KNIFE RADIUS	0.170000E-02
DIST TO CONTACT	0.000000E+00
BETA	20.0000
PRESSURE RATIO	1.07900
PRESSURE IN	35.0000
TEMPERATURE	900.000
MAX SEAL LENGTH	0.500000
MAX SEAL HEIGHT	0.250000

SUMMARY OF MINIMUM FLOW FOR VARIOUS SEAL CONFIGURATIONS

TYPE	DIR	NO. KNIVES	KT	KP	KH	SH	KTHETA	ROUGH	SEAL LENGTH	SEAL HEIGHT	MIN FLOW	
STRAIGHT		6	0.00900896	0.096040	0.096040		45.0444	30.00	0.48921		0.0085700	----OPTIMUM

CURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT See back
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) EDR 12131	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFWAL-TR-85-2103, Vol. IV
6a. NAME OF PERFORMING ORGANIZATION Allison Gas Turbine Division of General Motors Corp. — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Aero Propulsion Laboratory (AFWAL/POTX) Air Force Wright Aeronautical Laboratories
6c. ADDRESS (City, State and ZIP Code) P.O. Box 420 Indianapolis, Indiana 46206-0420	7b. ADDRESS (City, State and ZIP Code) Wright Patterson Air Force Base, OH 45433
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Aero Propulsion Laboratory — 8b. OFFICE SYMBOL (If applicable) AFWAL/POTX	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F33615-80-C-2014
8c. ADDRESS (City, State and ZIP Code) Air Force Wright Aeronautical Lab.(AFSC) Wright-Patterson AFB, OH 45433	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. 62203F; PROJECT NO. 3066; TASK NO. 10; WORK UNIT NO. 18
11. TITLE (Include Security Classification) Labyrinth Seal Analysis-Vol. IV (Unclassified)	

12. PERSONAL AUTHOR(S)
Raymond E. Chupp, Glenn F. Holle, Thomas E. Scott

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final Report	FROM 6/80 TO 5/85	January 1986	151

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Labyrinth seals, Rotating seals, Contactless seals, Gas path seals, Interstage seals, Air leakage in gas turbines
21	05		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A computer program has been written for the labyrinth seal Design Model which was developed to permit a rapid and comprehensive calculation for the leakage characteristics of conventional straight and stepped configurations. The user's manual for the labyrinth seal Design Model is presented in this volume. The manual contains a description of the "knife-to-knite" method of analysis and correlation of labyrinth seal data used in formulating the Design Model. General features and capabilities of the program are discussed. A description of the input data format and resulting output are included. The manual also includes a sample input and output dataset as well as a complete listing of the Fortran computer code.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Topham, Keith C., 1st Lt., USAF	22b. TELEPHONE NUMBER (Include Area Code) (513)255-6720	22c. OFFICE SYMBOL AFWAL/POTX

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

Unclassified
SECURITY CLASSIFICATION OF THIS PA

Block 3.

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The document availability was changed to EAR per DAA modified April 3, 2003, and Air Force communication WL/POTX W-PAFB dated December 11, 1992.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
October 2005

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Users' Manual for Labyrinth Seal Design Model (KTK)

5. FUNDING NUMBERS
WU–506–42–31–00
WU–590–21–11–00
NAS3–25644

6. AUTHOR(S)
Mechanical Technology, Inc.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Mechanical Technology, Inc.
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Latham, New York 12110

8. PERFORMING ORGANIZATION REPORT NUMBER
E–13627

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR—2003-212367
MTI 94TM6

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT
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Unclassified-Unlimited
Subject Category: 34
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12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

A computer program has been written for the labyrinth seal Design Model which was developed to permit a rapid and comprehensive calculation for the leakage characteristics of conventional straight and stepped configurations. The users' manual for the labyrinth seal Design Model is presented in this volume. The manual contains a description of the "knife-to-knife" method of analysis and correlation of labyrinth seal data used in formulating the Design Model. General features and capabilities of the program are discussed. A description of the input data format and resulting output are included. The manual also includes a sample input and output dataset.

14. SUBJECT TERMS
Labyrinth seals; Seal; Leakage; Rotating seals; Contactless seals; Gas path seals; Interstage seals; Air leakage in gas turbines; Users' manual

15. NUMBER OF PAGES
86

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	